The SZ effect as a probe of violent cluster mergers

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Purpose of This Talk

- Show (hopefully, give an observational proof) that ***high-spatial resolution*** (~10”) SZ mapping observations are a powerful probe of violent cluster mergers.

Collaborators (1998–2012)

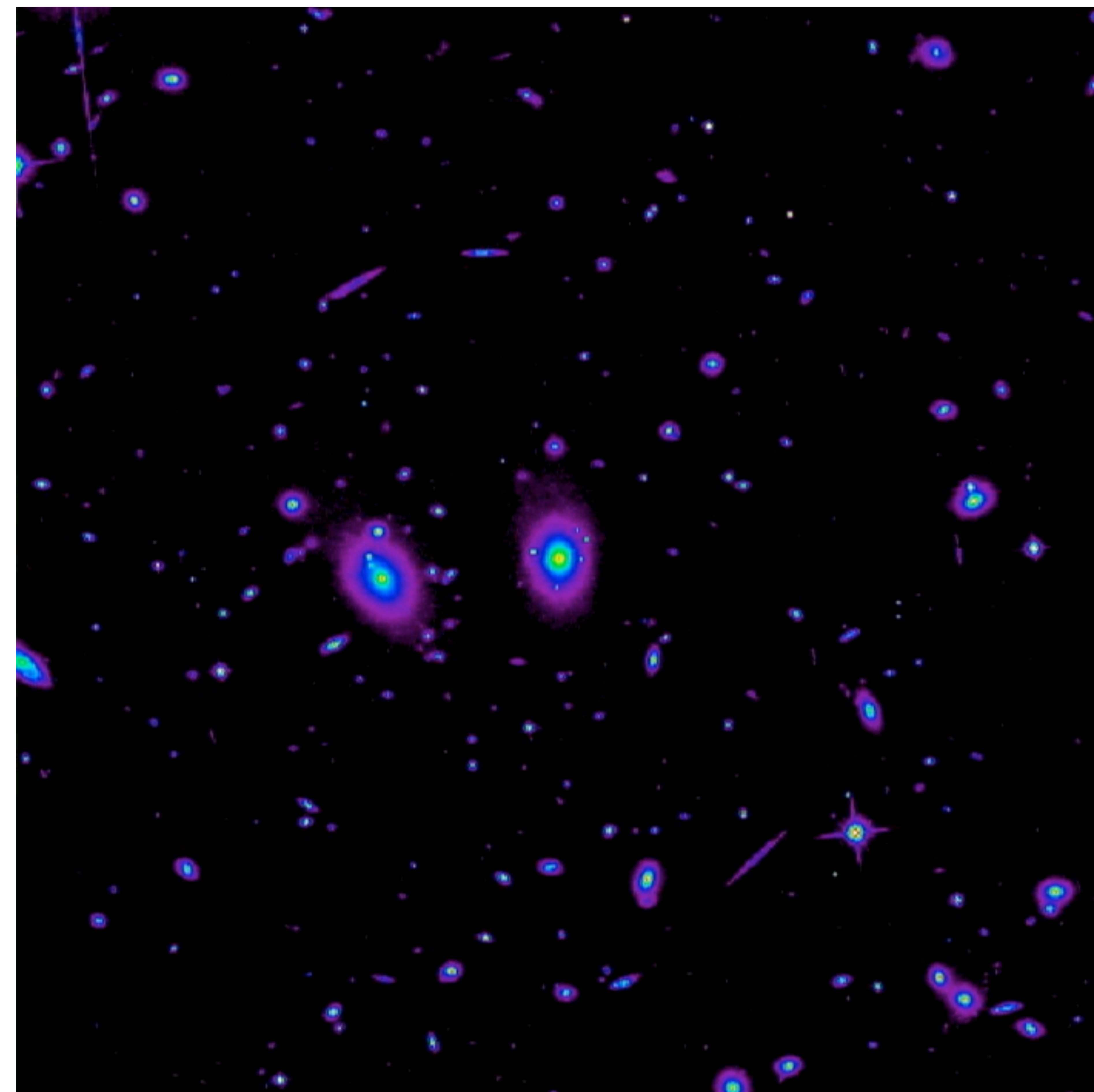
- Takuya Akahori (KASI)
- Makoto Hattori (Tohoku Univ.)
- Daisuke Iono (Nobeyama)
- Ryohei Kawabe (NAOJ)
- **Tetsu Kitayama** (Toho Univ.)
- Kotaro Kohno (Univ. of Tokyo)
- Nario Kuno (Nobeyama)
- Hiroshi Matsuo (NAOJ)
- Koichi Murase (Saitama Univ.)
- Tai Oshima (Nobeyama)
- **Naomi Ota** (Tokyo Univ. of Science)
- Shigehisa Takakuwa (ASIAA)
- Motokazu Takizawa (Yamagata Univ.)
- Takahiro Tsutsumi (NRAO)
- Sabine Schindler (Univ. of Innsbruck)
- Yasushi Suto (Univ. of Tokyo)
- Kenkichi Yamada (Toho Univ.)
- Kohji Yoshikawa (Univ. of Tsukuba)

Papers

- Komatsu et al., ApJL, 516, L1 (1999) [SCUBA@350GHz]
- Komatsu et al., PASJ, 53, 57 (2001) [NOBA@150GHz]
- Kitayama et al., PASJ, 56, 17 (2004) [Analysis w/ Chandra]
- Ota et al., A&A, 491, 363 (2008) [Suzaku]
- Yamada et al., PASJ, 64, 101 (2012) [ALMA Simulation]

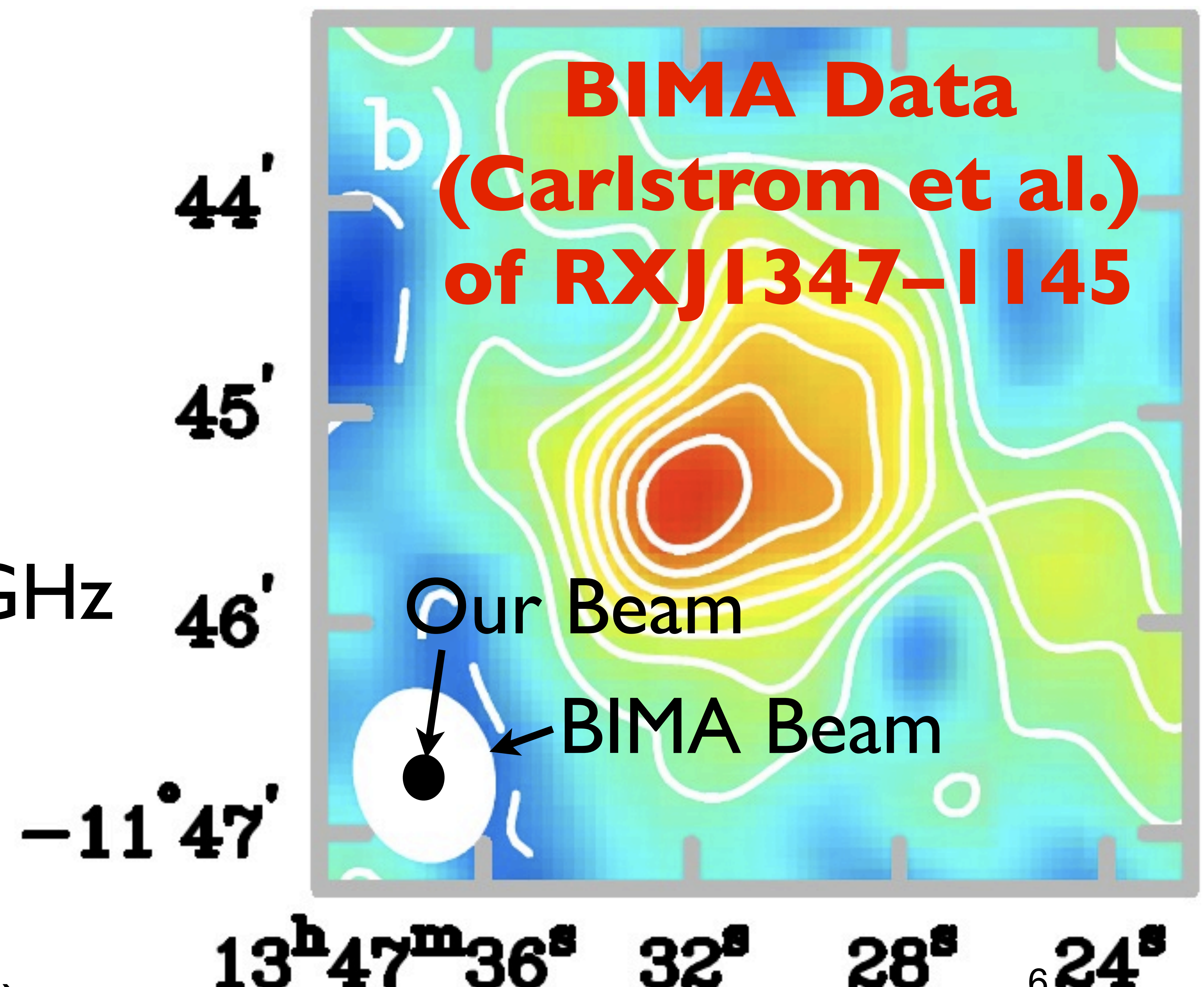
Target: Bright, Massive, and Compact

- RXJ1347–1145
- z=0.451 (10''=59 kpc)
- $L_{X,bol}$~2x10^{46} erg/s
- M_{tot}(<2Mpc)~1x$10^{15}$$M_{sun}$
- Cluster Mean T_X~13keV
- θ_{core}~8 arcsec (47 kpc)
- y~8x10^{-4}



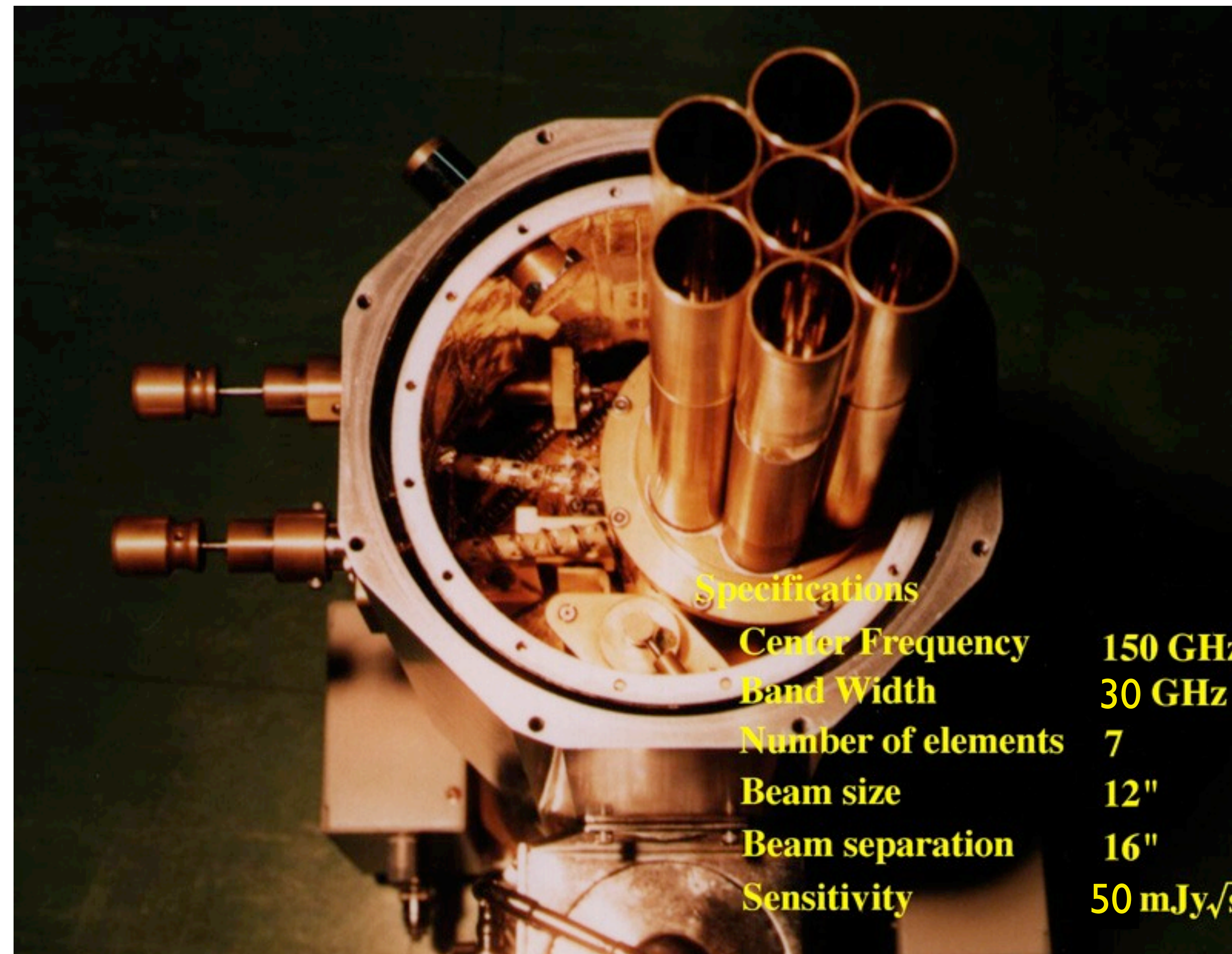
High Spatial Resolution SZ Mapping Observations

- **SCUBA**/JCMT@350GHz
  - ***15 arcsec*** FWHM Beam
  - Observed in 1998&1999
  - rms=5.3 mJy/beam (8 hours)
- **NOBA**/Nobeyama 45m@150GHz
  - ***13 arcsec*** FWHM Beam
  - Observed in 1999&2000
  - rms=1.6 mJy/beam (24 hours)



Nobeyama Bolometer Array

- NOBA = 7-element bolometer array working at λ=2mm
- Made by Nario Kuno (NRO) and Hiroshi Matsuo (NAOJ) in 1993

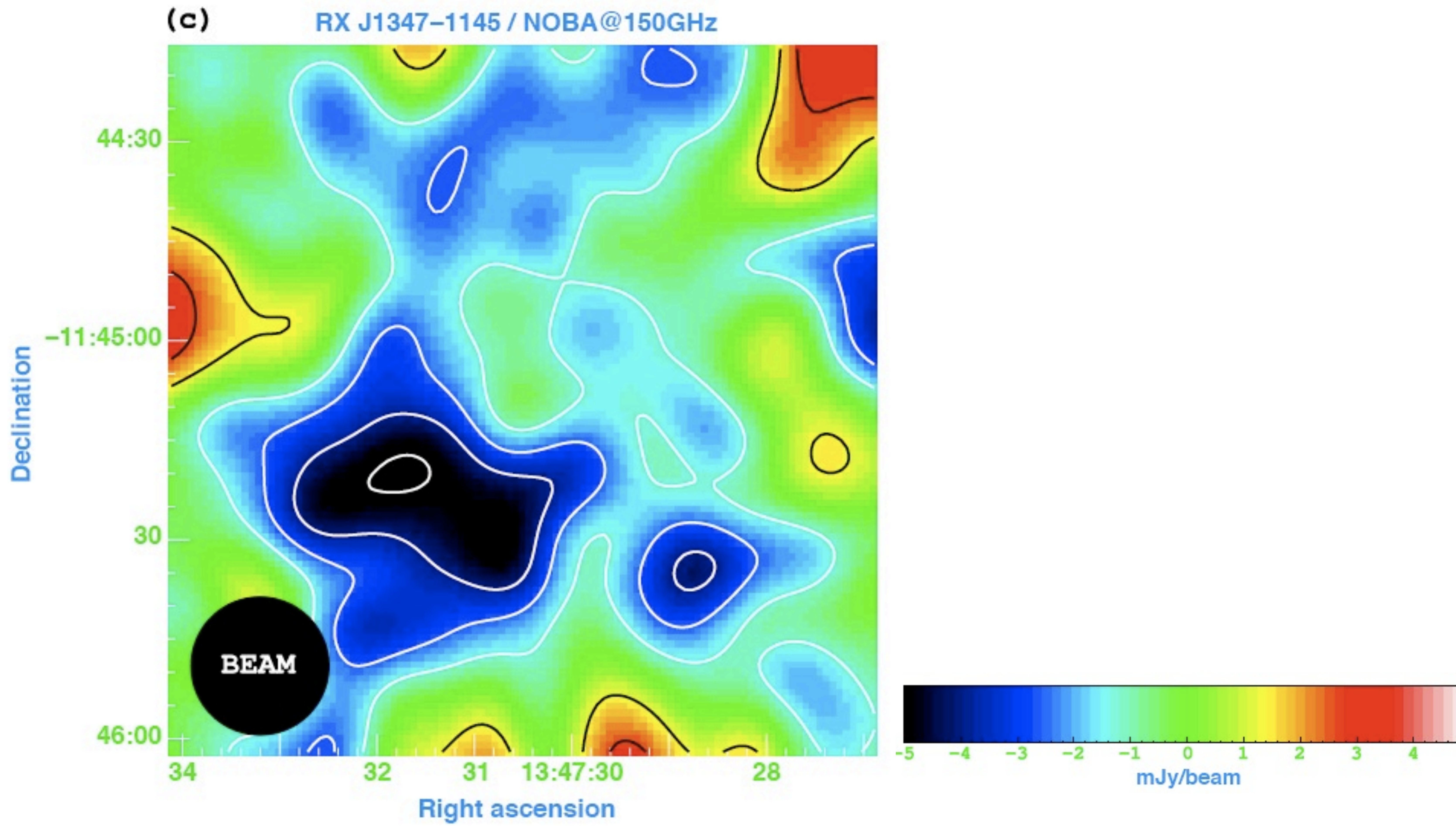


X-ray Observations

- **ROSAT**, HRI (Schindler et al. 1997)
  - Sensitive up to ***~2 keV***
  - 35.6 ks (HRI)
- **Chandra**, ACIS-S3 (Allen et al. 2002), ACIS-I (archived)
  - Sensitive up to ***~7 keV***
  - 18.9 ks (ACIS-S3), 56 ks (ACIS-I)
- **Suzaku**, XIS and HXD (Ota et al. 2008)
  - Sensitive up to ***~12 keV*** (XIS); ***~60 keV*** (HXD/PIN)
  - 149 ks (XIS), 122 ks (HXD)

Komatsu et al. (2001)

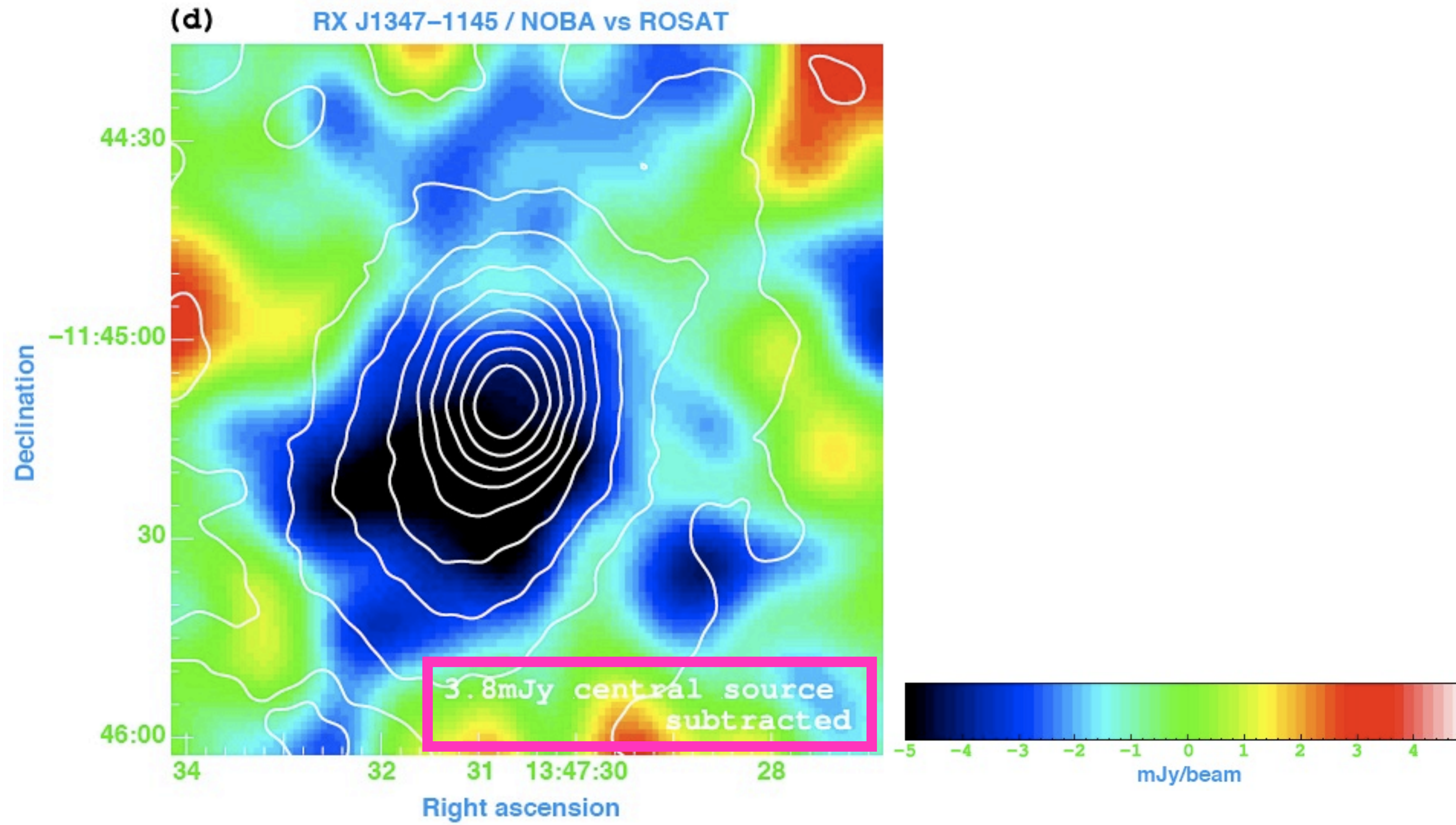
SZ "Hot Spot"



- Significant offset between the SZ peak and the cluster center.

Komatsu et al. (2001)

SZ saw it, but ROSAT missed



- ROSAT data indicated that this cluster was a relaxed, regular cluster. The SZ data was not consistent with that.

PASJ: Publ. Astron. Soc. Japan **53**, 57–62, 2001 February 25

Komatsu et al. (2001)

Substructures Revealed by the Sunyaev–Zel'dovich Effect at 150 GHz in a High-Resolution Map of RX J1347−1145

Eiichiro KOMATSU[1,2], Hiroshi MATSUO[3], Tetsu KITAYAMA[4], Makoto HATTORI[2],
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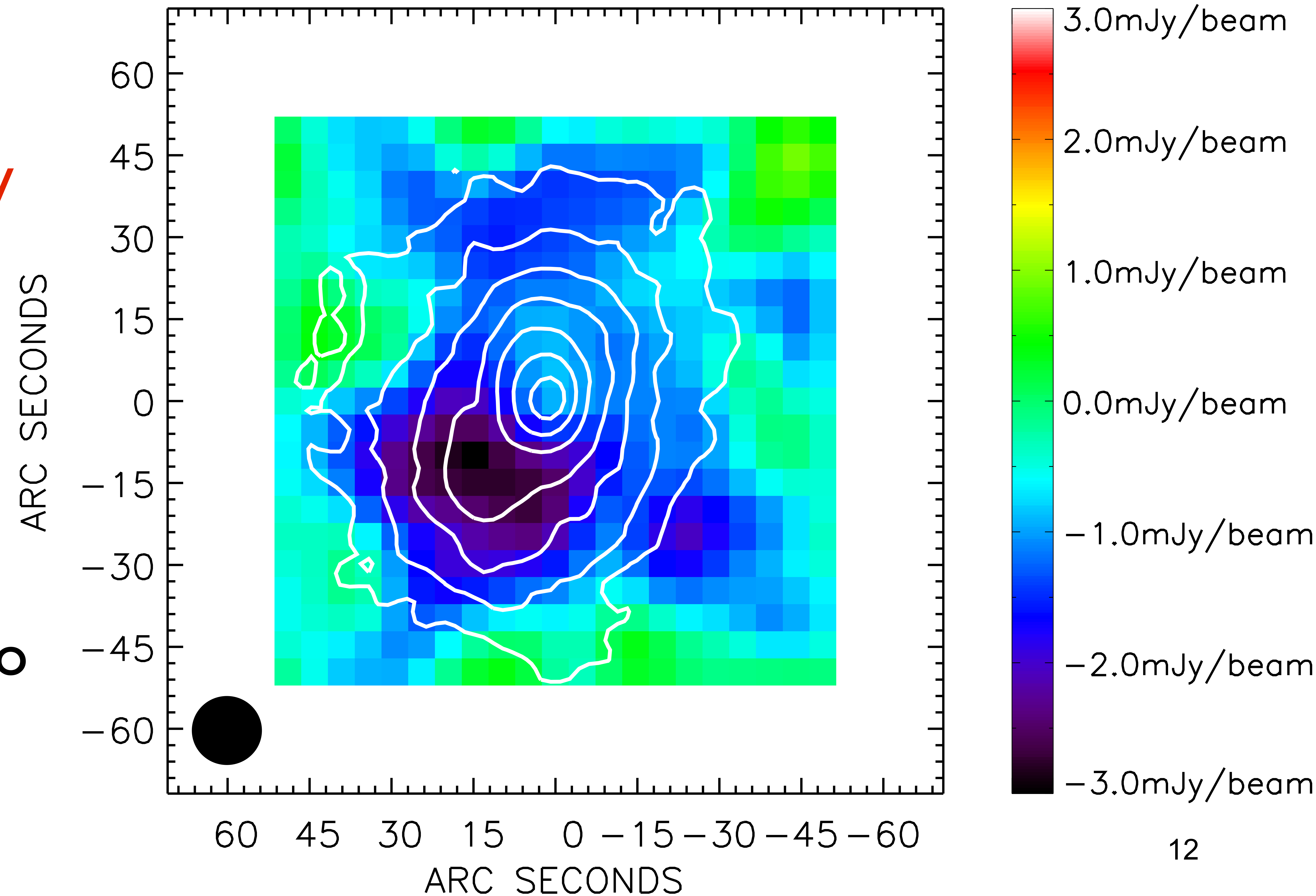
(Received 2000 June 20; accepted 2000 November 8)

Abstract

We report on mapping observations toward the region of the most luminous X-ray cluster, RX J1347−1145 ($z = 0.45$), through the Sunyaev–Zel'dovich effect at 21 GHz and 150 GHz with the Nobeyama 45-m telescope. While a low angular resolution image at 21 GHz (beam-size σ_{FWHM} of 76″) shows a consistent feature with the ROSAT/HRI X-ray image, a higher angular resolution image ($\sigma_{\mathrm{FWHM}} = 13''$) at 150 GHz reveals complex morphological structures of the cluster region, which cannot be simply described by the spherical isothermal β-model. If such inhomogeneous morphological features prove to be generic for high-redshift clusters, distance measurements to the clusters based on their Sunyaev–Zel'dovich data with low angular resolution imaging should be interpreted with caution.

Confirmed by Chandra

- Allen et al. (2002) estimated ~18 keV toward this direction from Chandra spectroscopy.
- But, Chandra is sensitive only up to ~7(1+z)=10 keV...



X-ray + SZ Joint

- The SZ effect is sensitive to arbitrarily high temperature.
- X-ray spectroscopy is not.
- Combine the X-ray **brightness** and the SZ **brightness** to derive the electron temperature:
  - I_{SZ} is proportional to $n_e T_e L$, I_X is proportional to $n_e^2 \Lambda(T_e) L$ -> Solve for T_e (and L)
  - **No X-ray spectroscopy is used**

PASJ: Publ. Astron. Soc. Japan **56**, 17–28, 2004 February 25

Kitayama et al. (2004)

Exploring Cluster Physics with High-Resolution Sunyaev–Zel'dovich Effect Images and X-Ray Data: The Case of the Most X-Ray-Luminous Galaxy Cluster RX J1347−1145

Tetsu KITAYAMA,[1] Eiichiro KOMATSU,[2,3] Naomi OTA,[4] Takeshi KUWABARA,[5] Yasushi SUTO,[5,6]
Kohji YOSHIKAWA,[5] Makoto HATTORI,[7] and Hiroshi MATSUO[8]

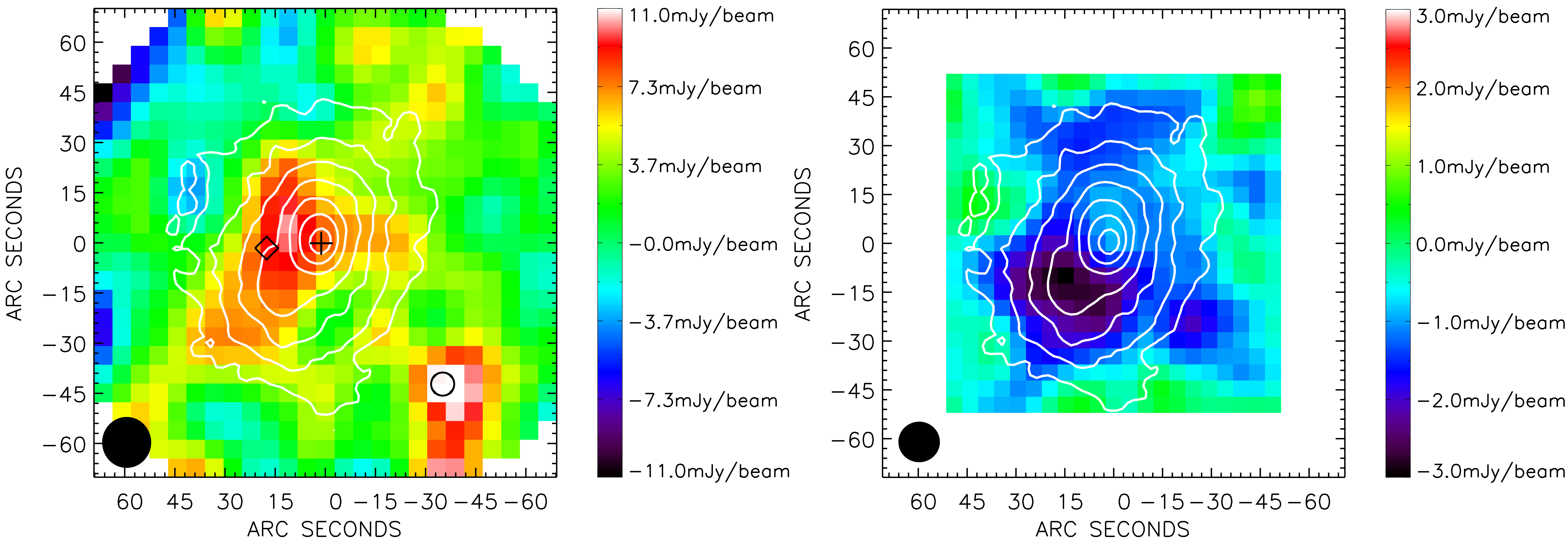
(Received 2003 October 1; accepted 2003 November 25)

Abstract

Foreseeing the era of high spatial resolution measurements of the Sunyaev–Zel'dovich effect (SZE) in clusters of galaxies, we present a prototype analysis of this sort combined with Chandra X-ray data. It is applied specifically to RX J1347−1145 at $z = 0.451$, the most X-ray-luminous galaxy cluster known, for which the highest resolution SZE and X-ray images are currently available. We demonstrate that the combined analysis yields a unique probe of complex structures in the intracluster medium, offering determinations of their temperature, density, and line-of-sight extent. For a subclump in RX J1347−1145, previously discovered in our SZE map, the temperature inferred after removing the foreground and background components is well in excess of 20 keV, indicating that the cluster has recently undergone a violent merger. Excluding the region around this subclump, the SZE signals in submillimeter to centimeter bands (350, 150, and 21 GHz) are all consistent with those expected from Chandra X-ray observations. We further present a temperature deprojection technique based on the SZE and X-ray images, without any knowledge of spatially resolved X-ray spectroscopy. The methodology presented here will be applicable to a statistical sample of clusters available in the future SZE surveys.

Komatsu et al. (1999, 2001); Kitayama et al. (2004)

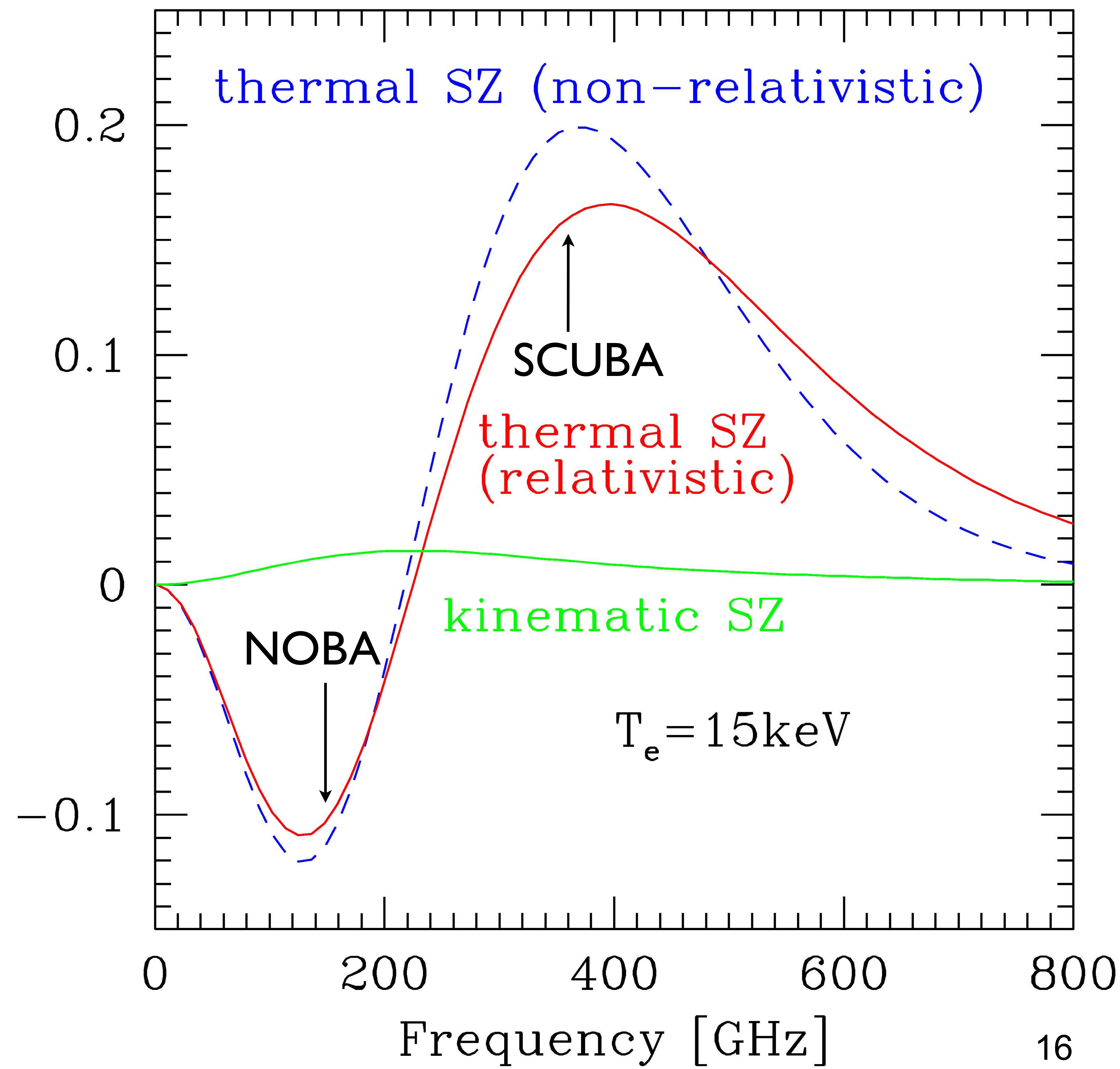
Images of the SZ data



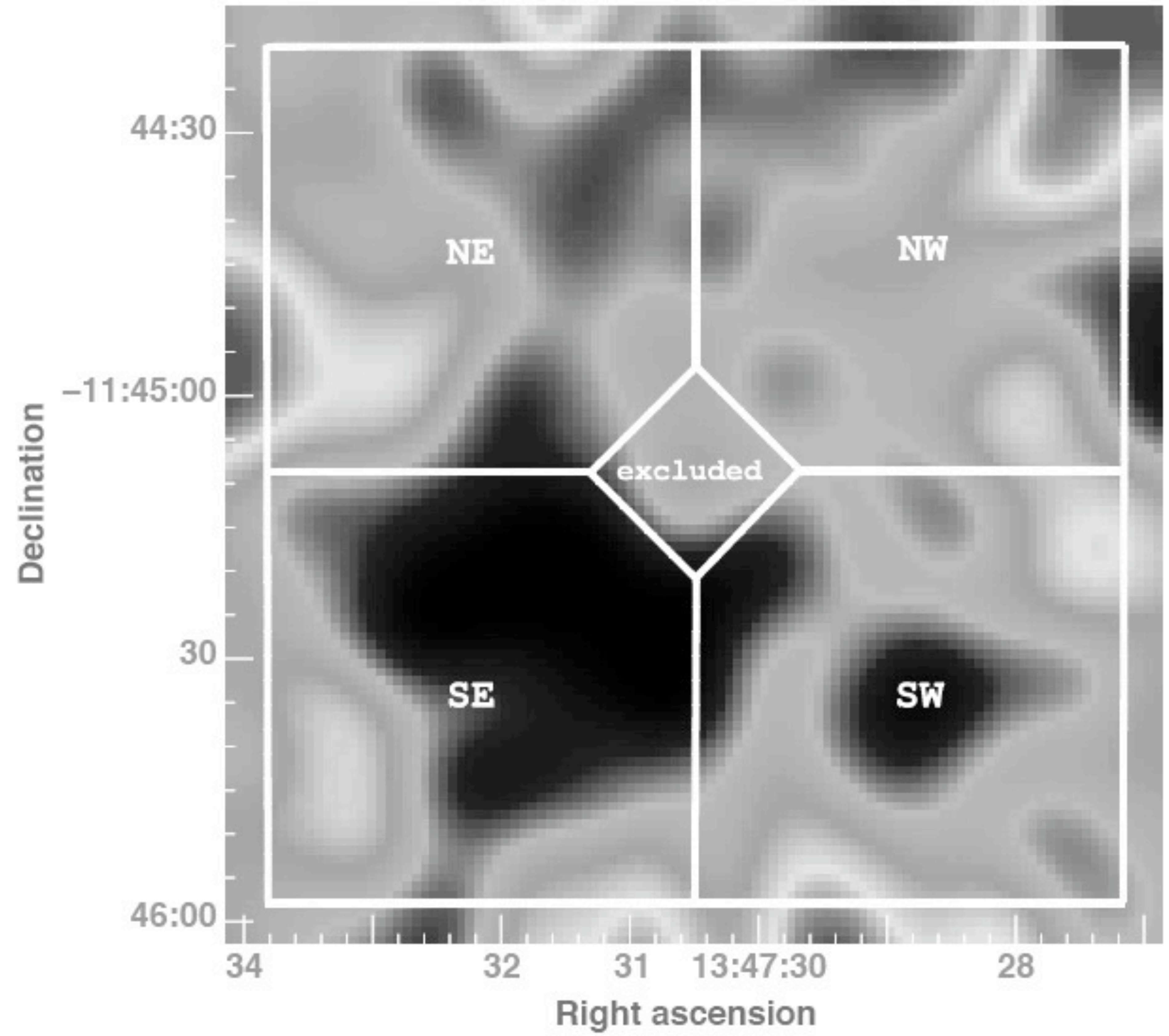
- Spatially resolved SZ images in 350 GHz (increment) and 150 GHz (decrement)

Relativistic Correction

- At such a high T_e that we are going to deal with (~20 keV), the relativistic correction must be taken into account.
- The suppression of the signal due to the relativistic correction diminishes the SZ at 350GHz more than that at 150GHz.



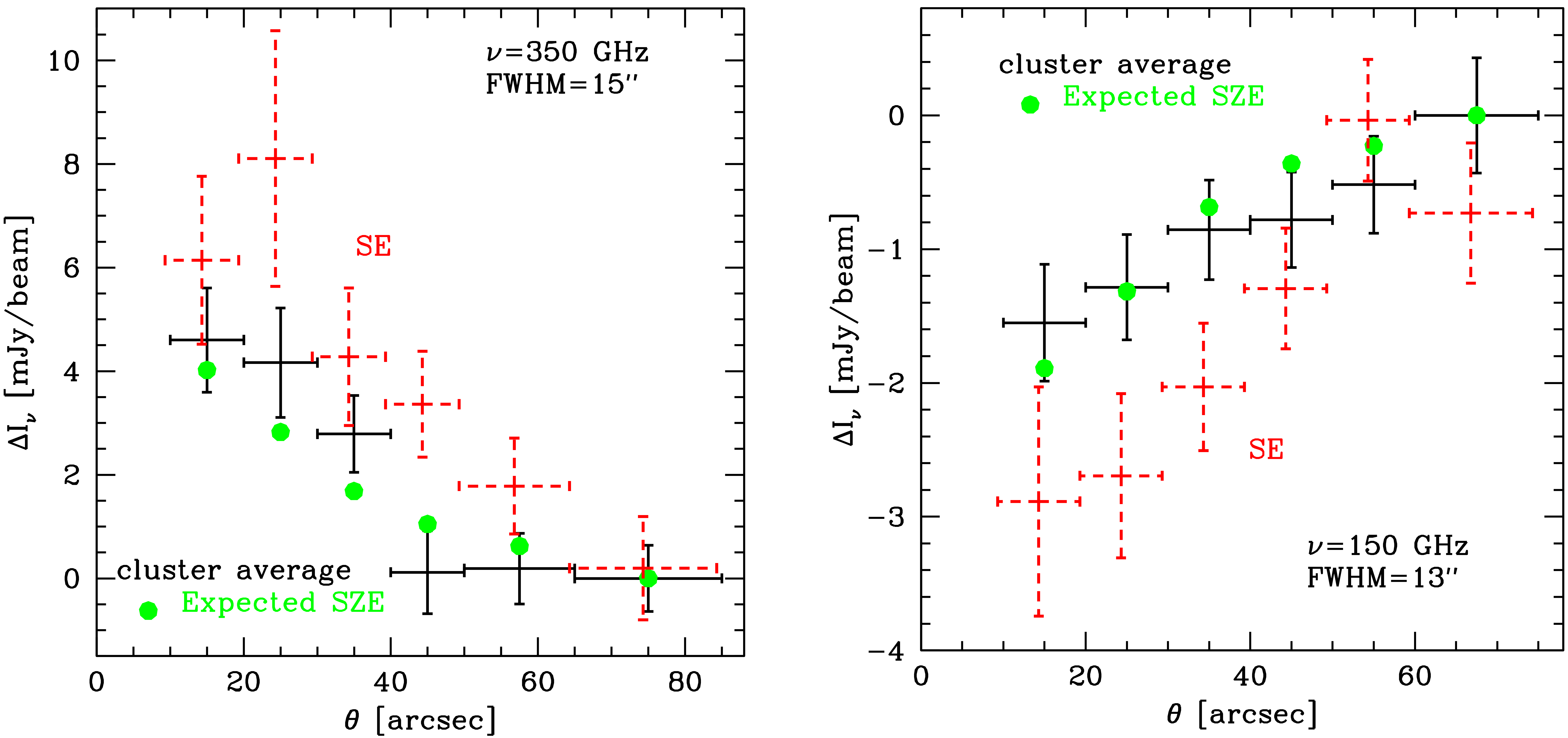
“SE” (South-East) Quadrant



- We exclude the central part that is contaminated by the ~4mJy point source, and treat the SE quadrant separately from the rest of the cluster (which we shall call the “ambient component”).

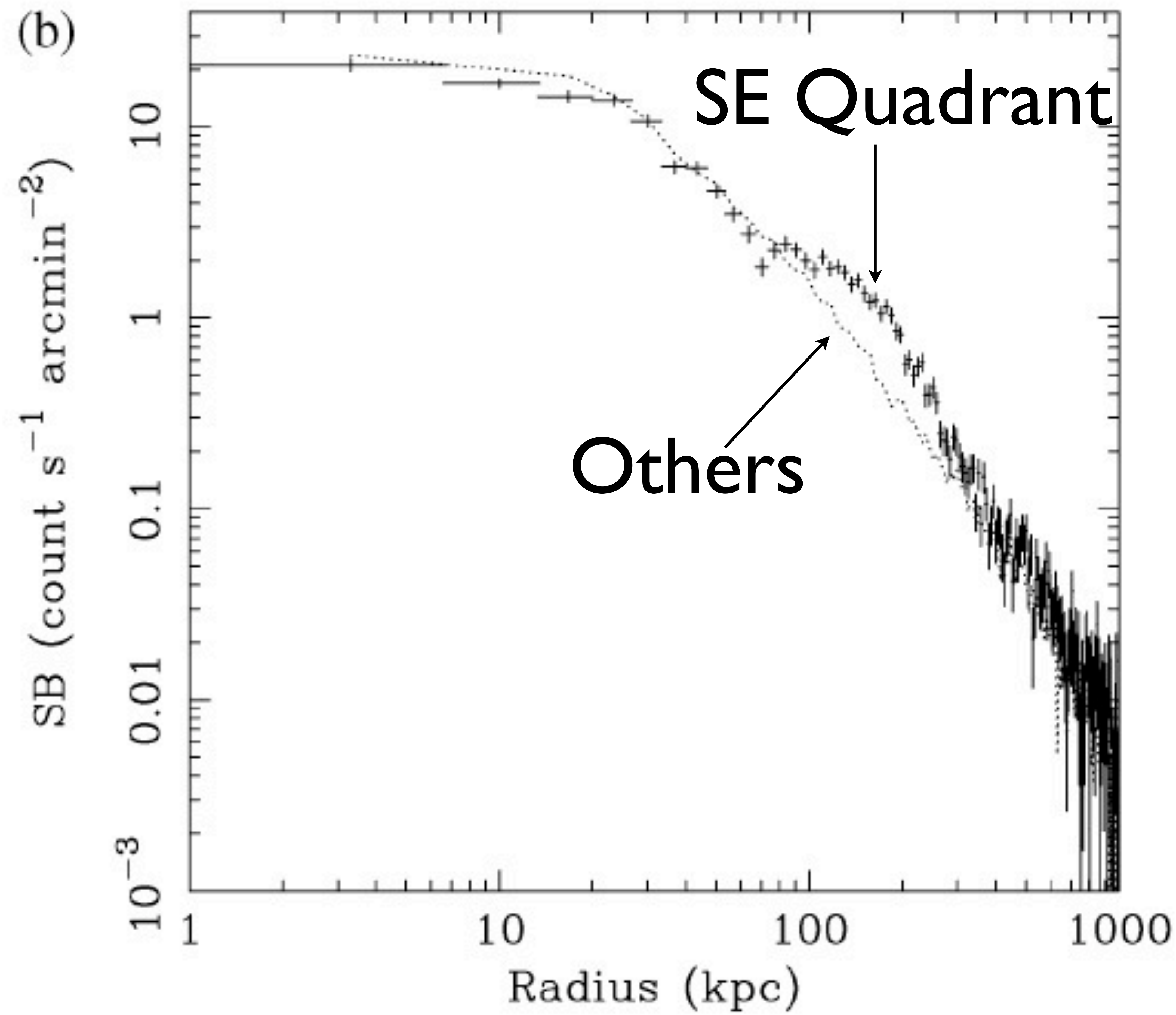
Komatsu et al. (1999, 2001); Kitayama et al. (2004)

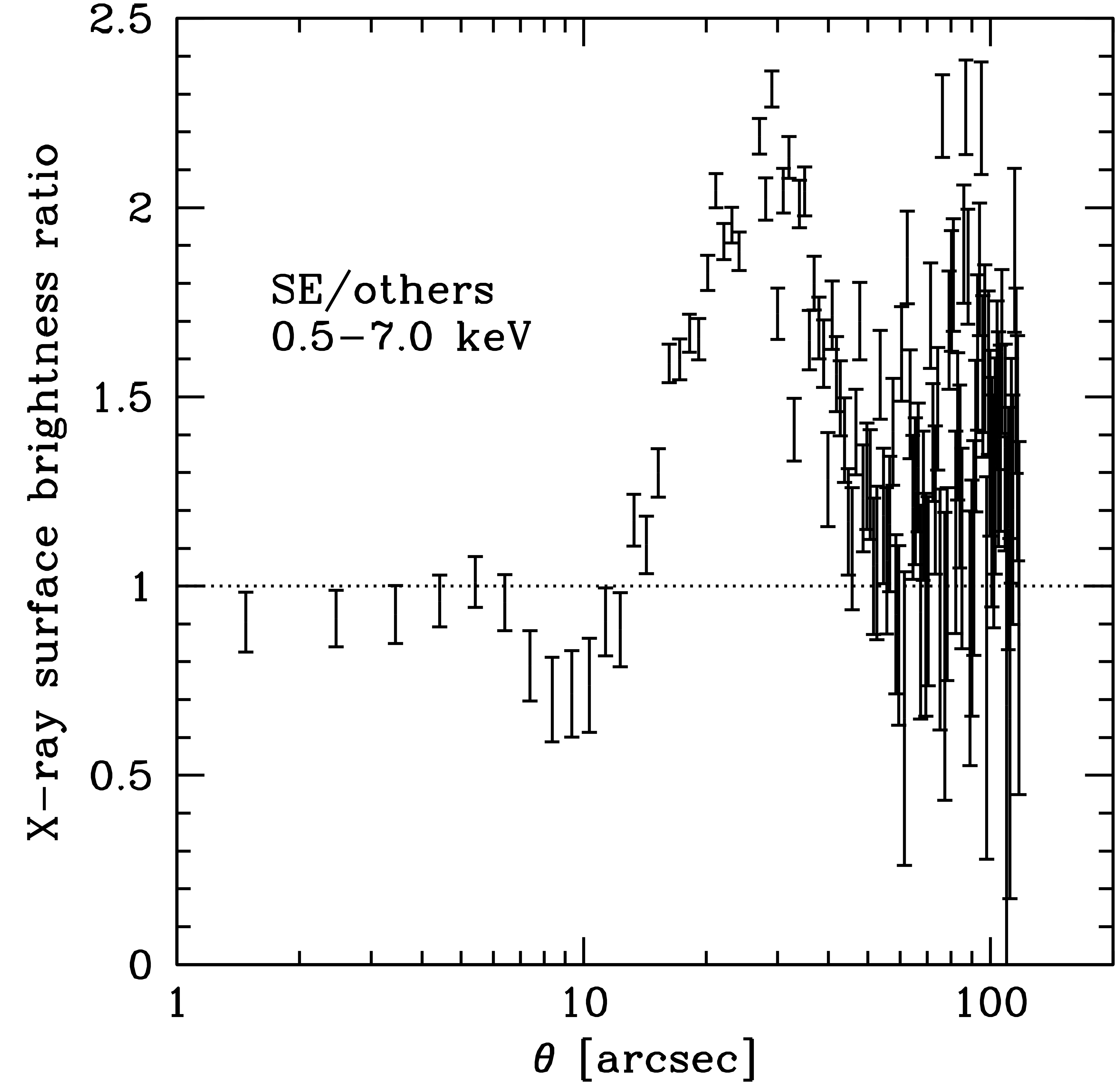
SZ Radial Profiles



- The excess SZ in the South-East quadrant is clearly seen.

X-ray Radial Profile

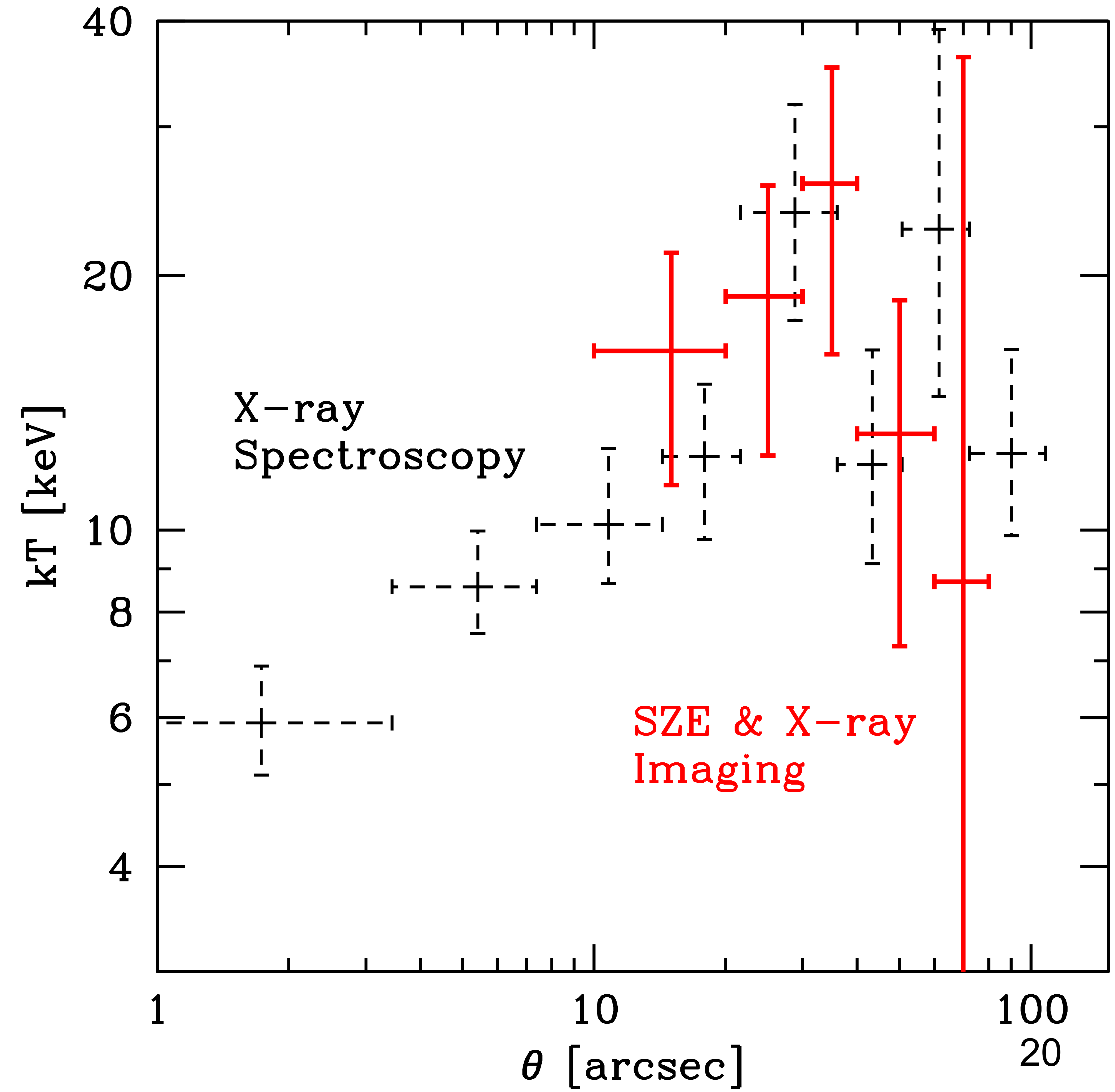




- The Chandra data also show the clear excess at ~20”.

Temperature Deprojection (Ambient Component)

- SE quadrant is excluded.
- **Black**: the temperature profile measured from the Chandra X-ray spectroscopy.
- **Red**: the temperature profile measured from the spatially resolved SZ data + X-ray imaging, without spectroscopy.

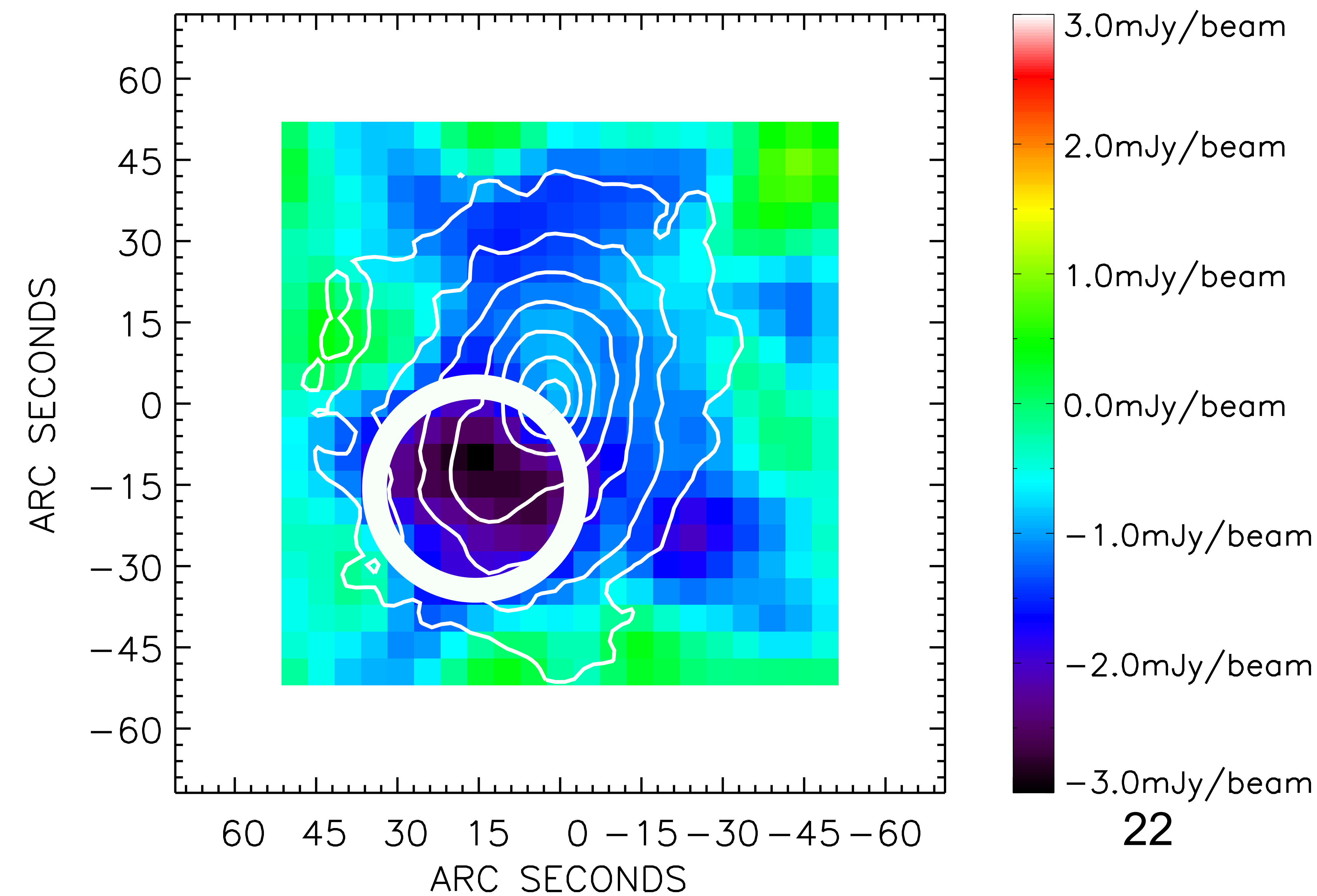


What is this good for?

- Spatially-resolved SZ + X-ray surface brightness observations give you the temperature profile, *without spatially-resolved spectroscopic observations.*
- A powerful way of determining the temperature profiles from high-z clusters, where you may not get enough X-ray photons to do the spatially-resolved spectroscopy!
- Why need temperature profiles? For determining accurate *hydrostatic masses*.

Excess Component: Derived Parameters

- With the SZ data (150&350GHz) and the Chandra X-ray data
- kT_{excess}=28.5±7.3 keV
- n_{excess}=(1.49±0.59)x10^{-2} cm^{-3}
- L_{excess}=240±183 kpc
- y_{excess}~4x10^{-4}
- M_{gas}~2x10^{12} M_{sun}



Characterizing a merger in RXJ1347-1145

- A calculation of the shock (Rankine-Hugoniot condition) with:
  - pre-shock temp=kT_1=12.7keV; post-shock=kT_2=28.5keV
  - pre-shock density=ρ_1=free; post-shock=ρ_2=0.015 cm^{-3}
  - gamma=5/3

$$\frac{T_1\rho_1}{T_2\rho_2} = \frac{p_1}{p_2} = \frac{(\gamma+1)-(\gamma-1)\frac{\rho 2}{\rho 1}}{(\gamma+1)\frac{\rho 2}{\rho 1}-(\gamma-1)}$$

- Solution: ρ_1~1/2.4 of the post-shock density

Characterizing a merger in RXJ1347-1145

- The Mach number of the pre-shock gas ~ 2, and the velocities of the pre-shock and post-shock gas are 3900 km/s & 1600 km/s.
  - Rather high velocity!
- For more detailed modeling in the context of "gas sloshing," see Johnson et al. (2012)

A Big Question

- **Do you believe these results?**
- **<u>This was the only dataset</u>** [before 2010] for which the spatially-resolved, high-resolution SZ data were available, and used to extract the cluster physics.
- Can we get the same results using the X-ray data alone?
    - For Chandra, the answer is no: not enough sensitivity at >7(1+z)keV.
    - **Suzaku can do this.**

A Punch Line

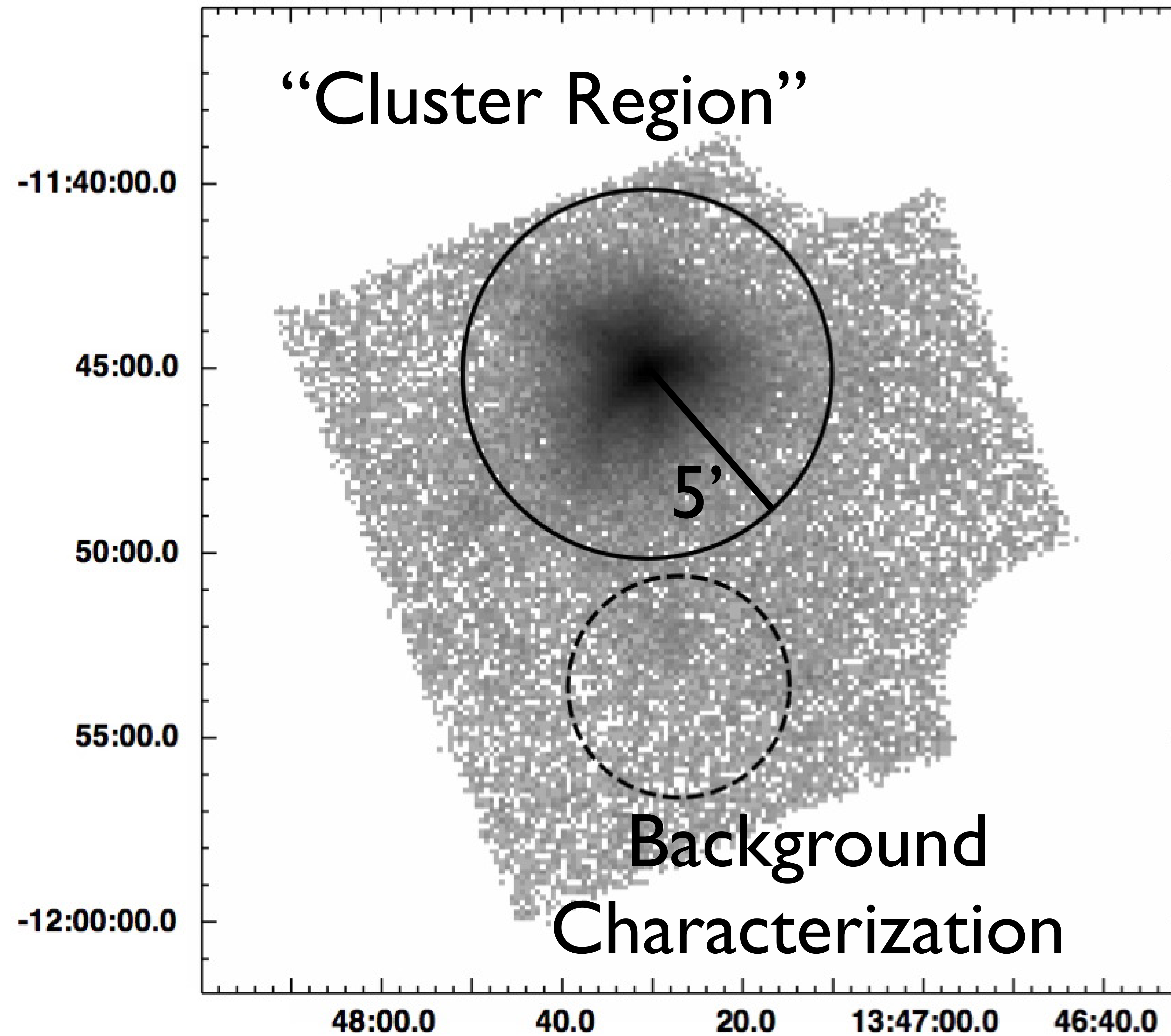
- With Suzaku's improved sensitivity at ~10 keV, we could determine the temperature of the excess component using the **X-ray data only**.
- And, the results are in an excellent agreement with the SZ+Chandra analysis.
- *Ota et al., A&A, 491, 363 (2008)*

Suzaku Telescope

- Japan-US X-ray satellite, formally known as ASTRO-E2
- X-ray Imaging Spectrometer (XIS)
  - X-ray CCD cameras; FOV=18'x18'; Beam=2'
  - Three with 0.4–**12**keV; one with 0.2–**12**keV
  - Energy resolution~160eV at 6keV
- Hard X-ray Detector (HXD)
  - One with **10–60**keV; another with 40–600keV
  - FOV=30'x30' for 10–60keV, no imaging capability

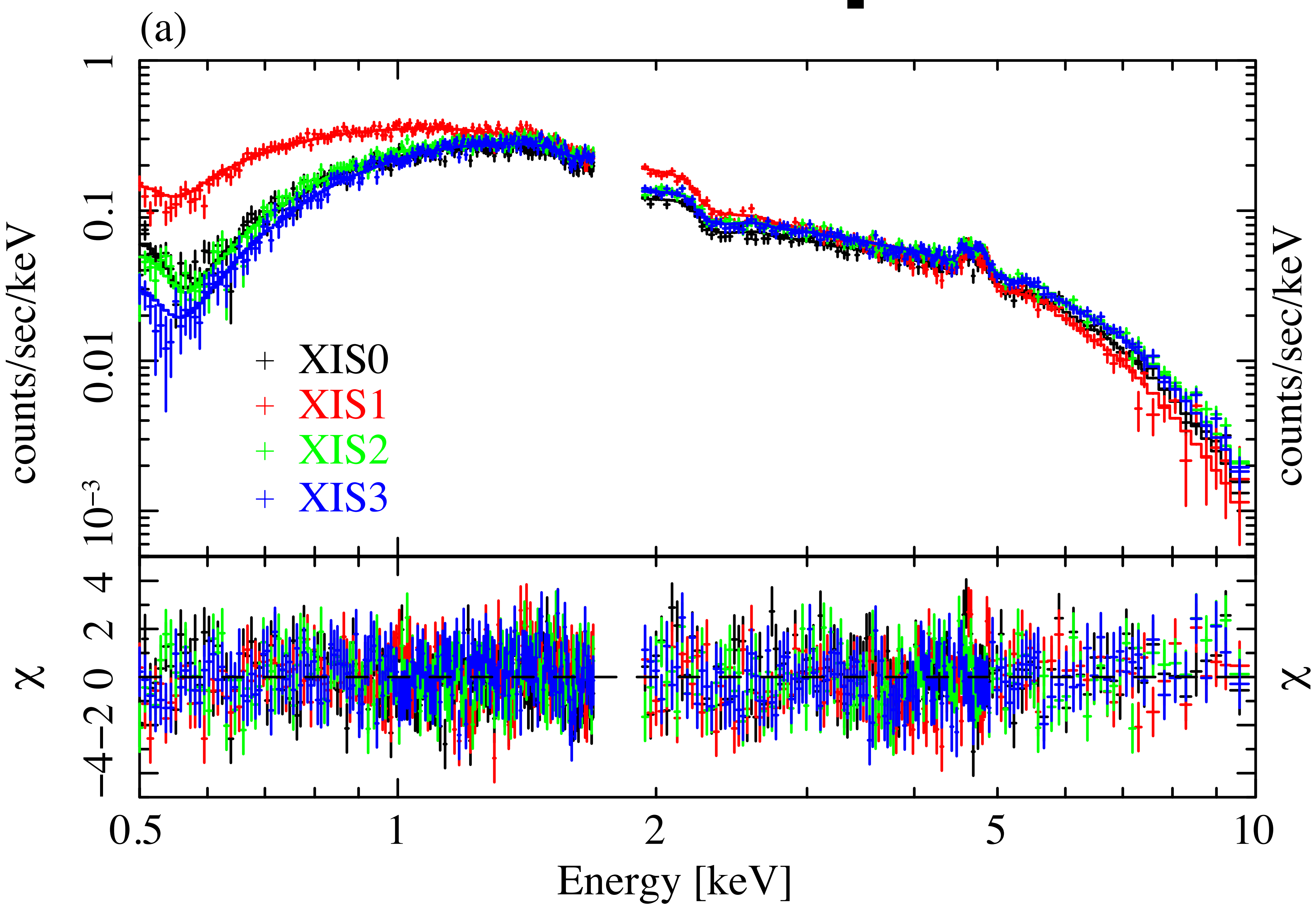
XIS Image of RXJ1347–1145

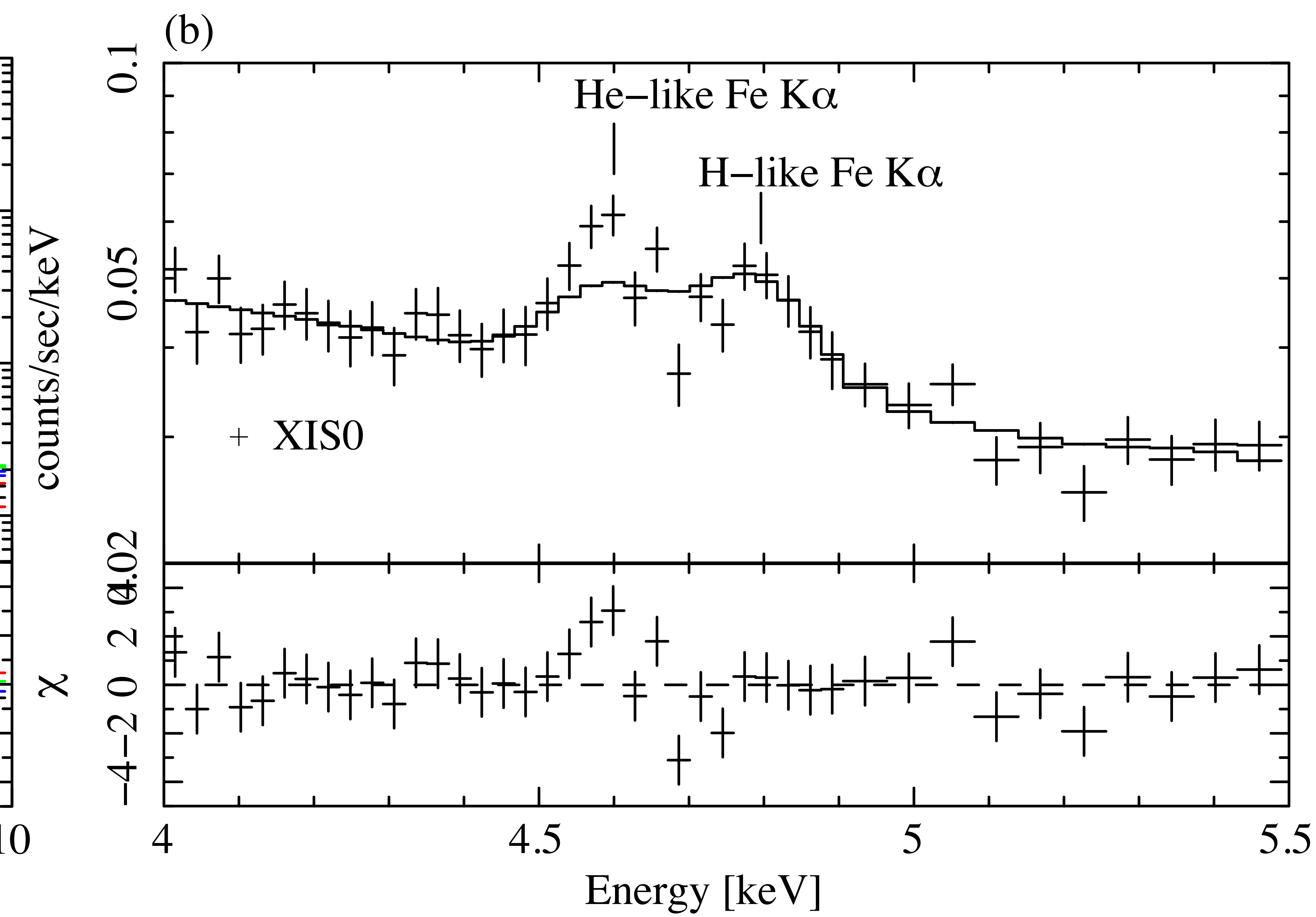
- From one of the XIS cameras, in 0.5–10keV
- FOV=18'x18'



XIS Spectra

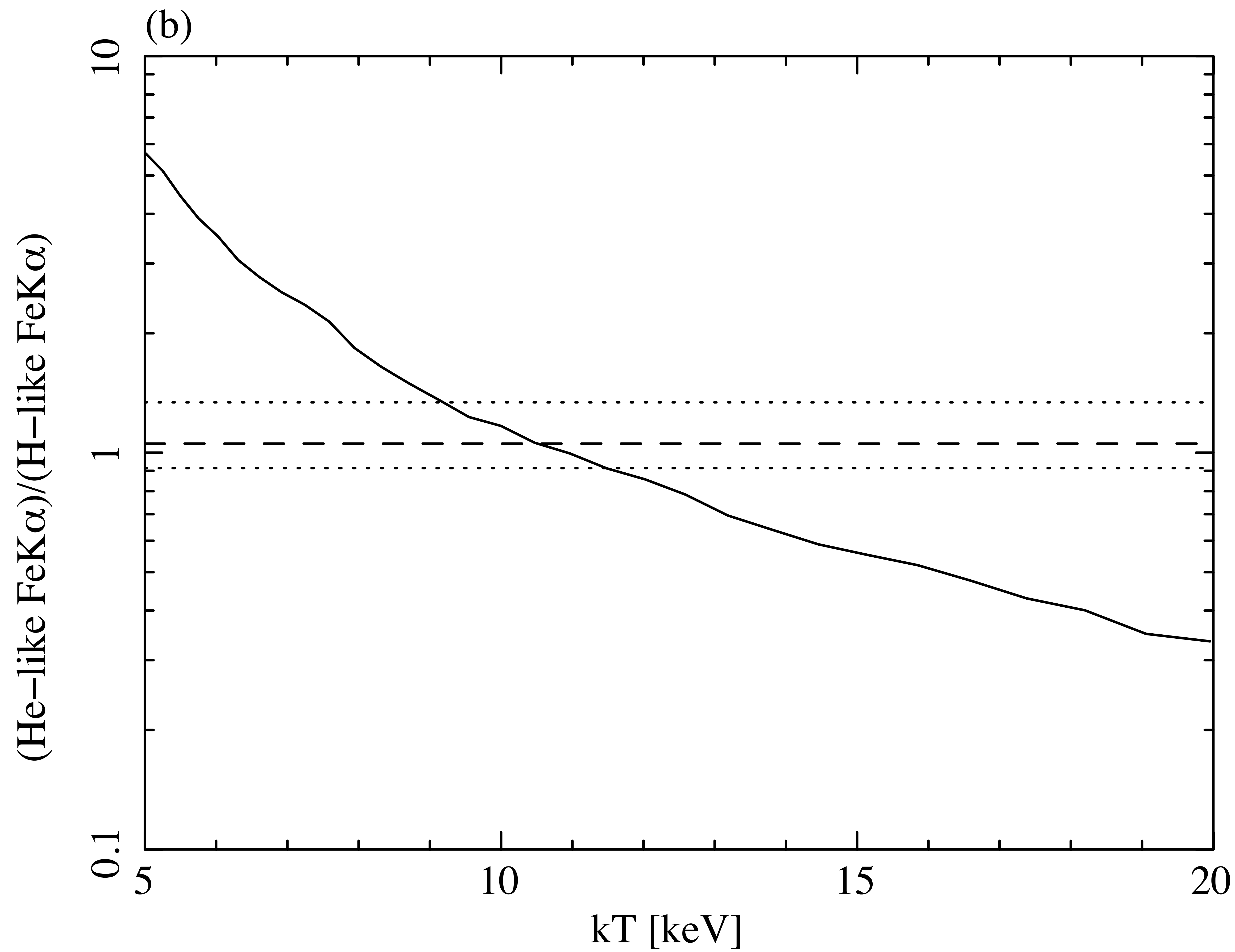
H-like: rest frame 6.9 keV
He-like: rest frame 6.7 keV





- Single-temperature fit yields $kT_e = 12.86^{+0.08}_{-0.25}$ keV
- But, it fails to fit the Fe line ratios - $\chi^2 = 1320/1198$
  - The single-temperature model is rejected at 99.3% CL

Temperature From Line Ratio

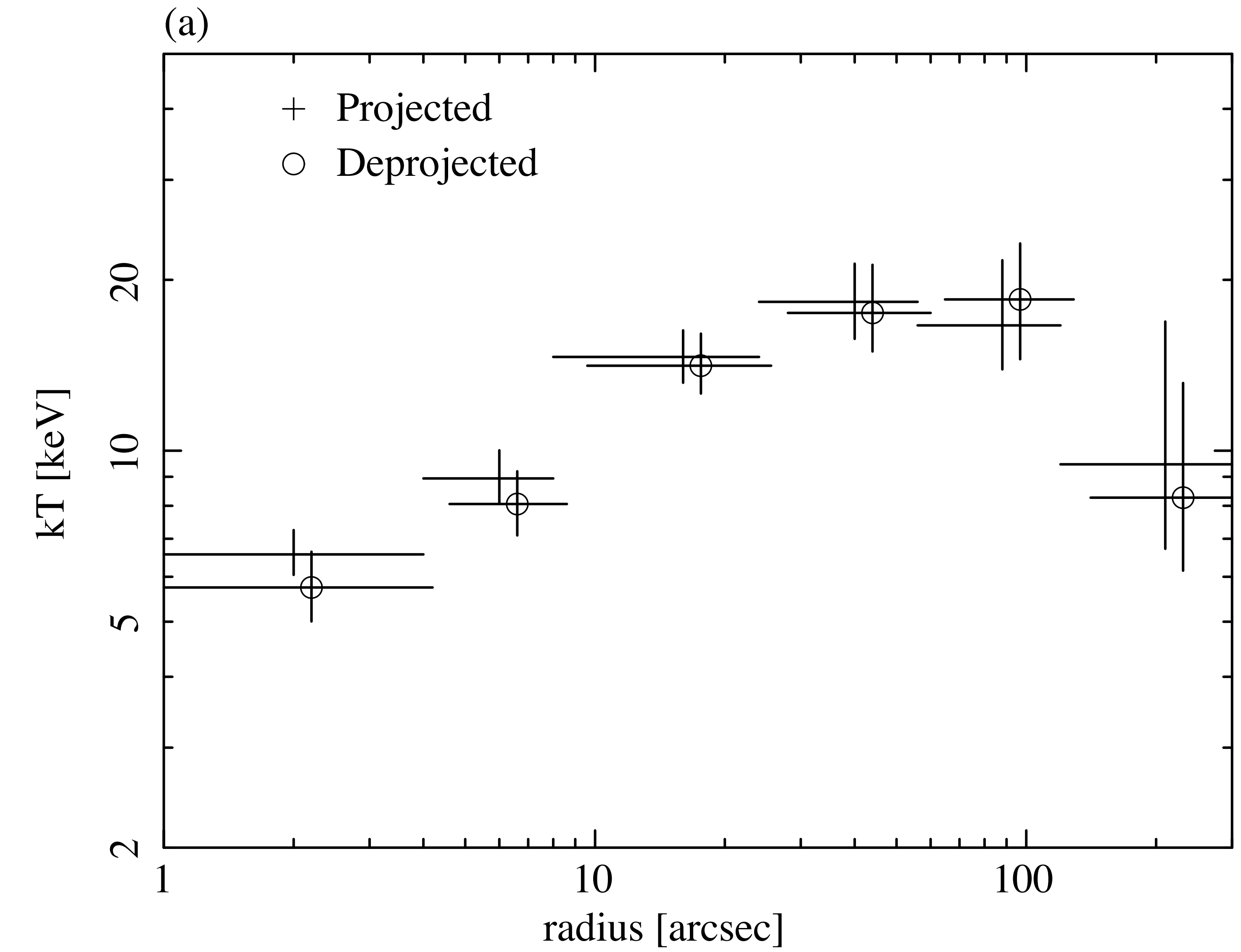


- $kT_e = 10.4^{+1.0}_{-1.3}$ keV - significantly cooler than the single-temperature fit, $12.86^{+0.08}_{-0.25}$ keV.

More Detailed Modeling

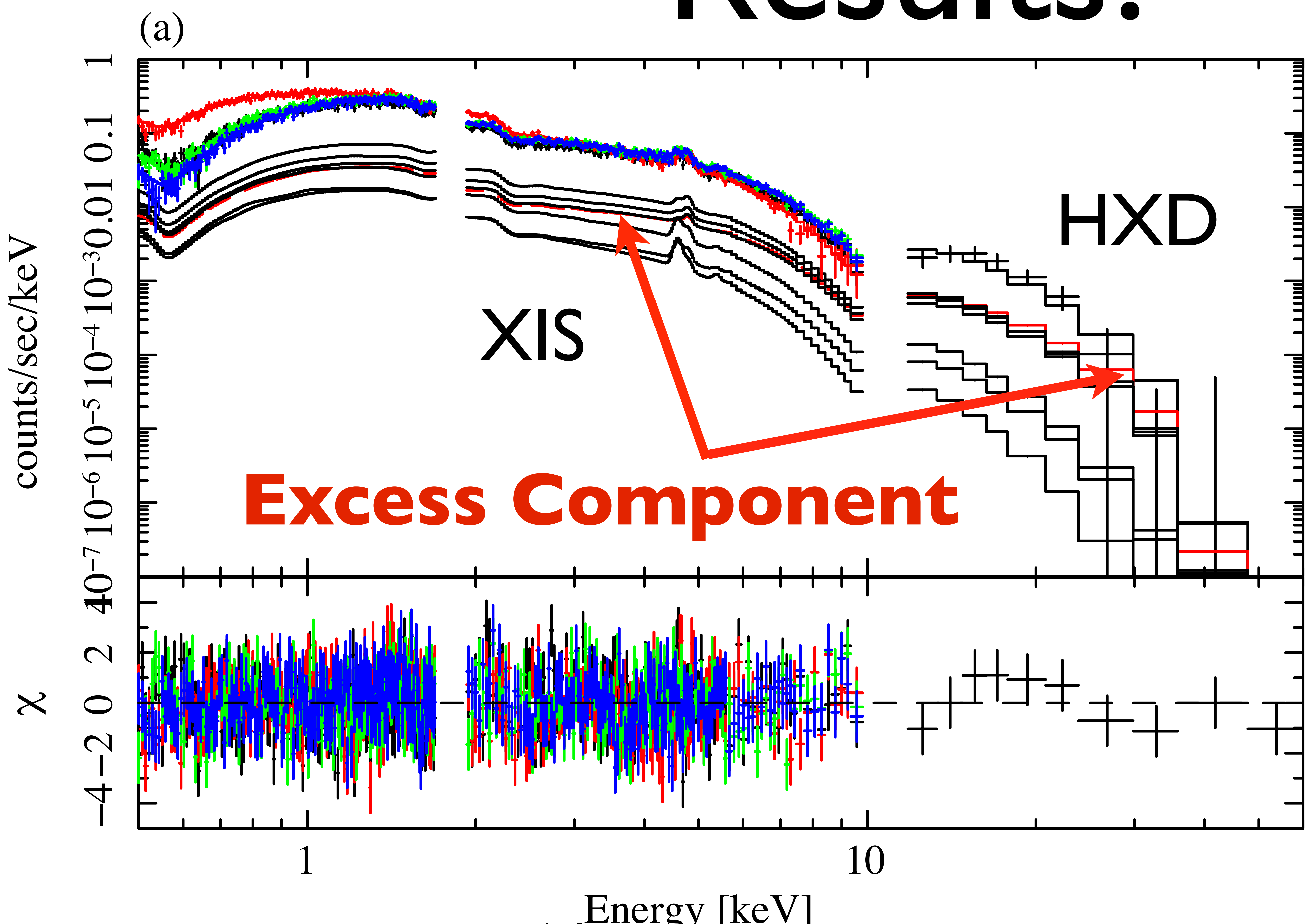
- We tried the next-simplest model: two-temperature model, but it did not work very well either.
- We know why: RXJ1347-1145 is more complicated than the two-component model.
  - The second component is localized, rather than distributed over the entire cluster.
- A joint Chandra/Suzaku analysis allows us to take advantage of the Chandra's spatial resolution and Suzaku's spectroscopic sensitivity.

“Subtract Chandra from Suzaku”



- To make a long story short:
  - We use the Chandra data outside of the excess region (SE region) to get the model for the ambient gas.
    - 6 components fit to 6 radial bins from 0” to 300”.
  - Then, subtract this ambient model from the Suzaku data.
  - Finally, fit the thermal plasma model to the residual.
  - And...

Results!



HXD data are consistent with the thermal model; we did not find evidence for non-thermal emission.

- $kT_{excess}=25.3^{+6.1}_{-4.5}$ keV; $n_{excess}=(1.6\pm0.2)\times10^{-2}$ cm^{-3}
  - Consistent with SZ+Chandra:
    - $kT_{excess}=28.5\pm7.3$ keV, $n_{excess}=(1.49\pm0.59)\times10^{-2}$ cm^{-3}

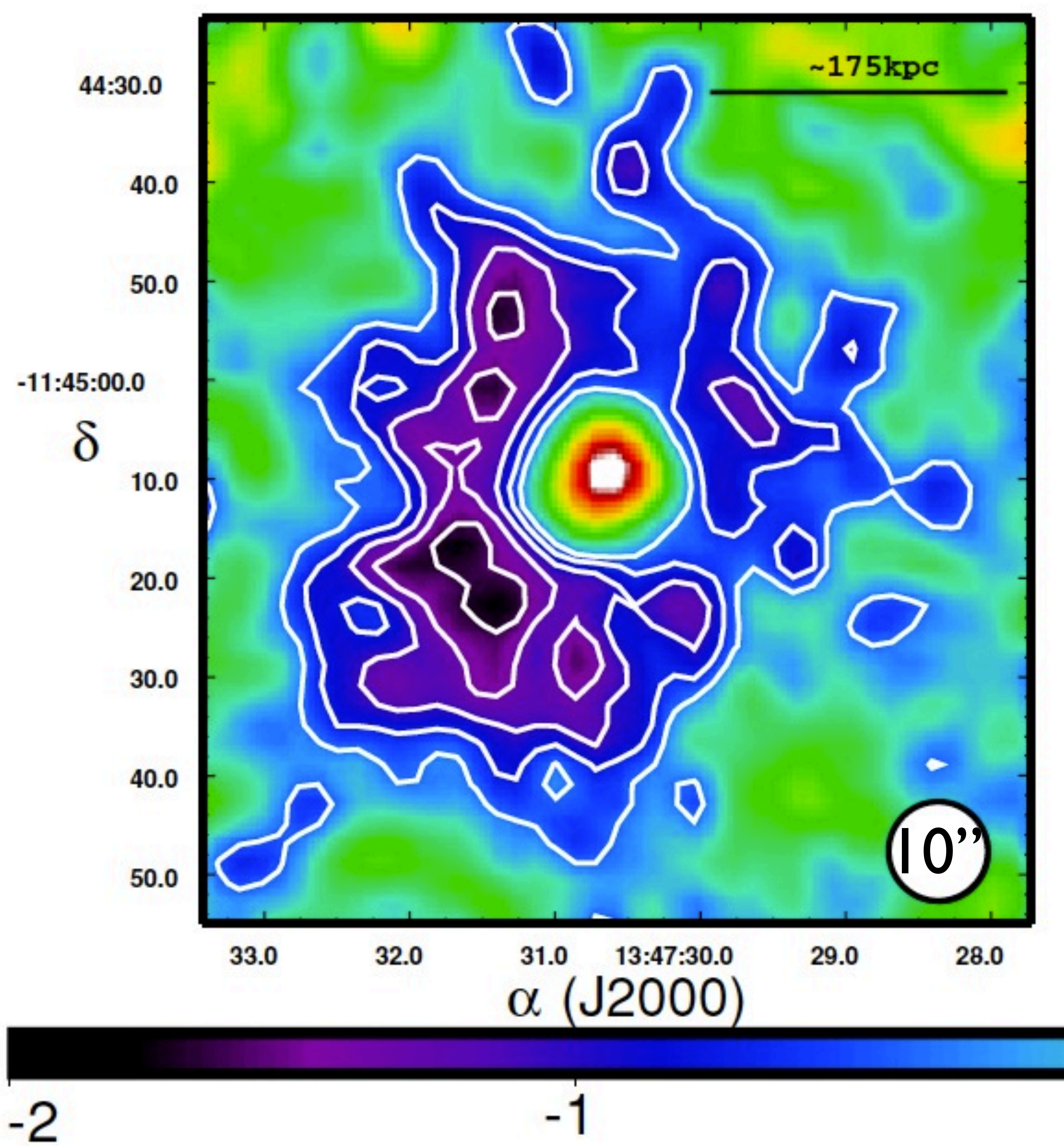
Proof of Principle

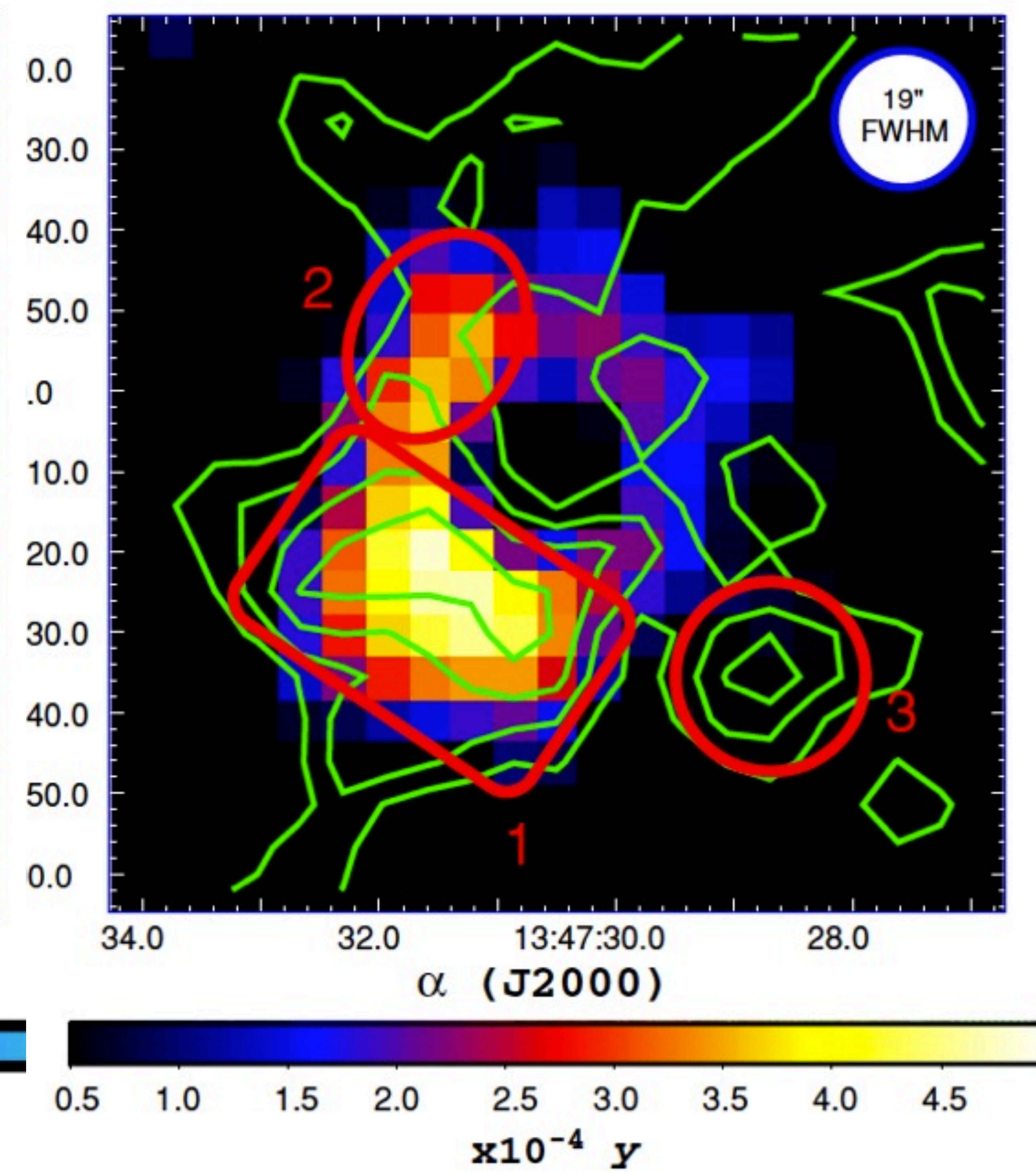
- So, *finally*, we have a proof:
  - Yes, *the high-spatial resolution SZ mapping combined with the X-ray surface brightness indeed gives the correct result.*
- And, we have found a candidate for the *hottest* gas clump known so far!

Lessons

- X-ray data may not capture (or measure) the temperature of very hot (>20 keV) components, if their band is limited to <10 keV.
- SZ is sensitive to arbitrarily high temperatures, which makes it *an ideal probe of violent cluster mergers*.
- As an added bonus, it should allow us to determine temperature profiles, hence masses, of clusters in a high-redshift universe, where X-ray spectroscopic observations are difficult.

...and, directly confirmed by MUSTANG on GBT in 2010



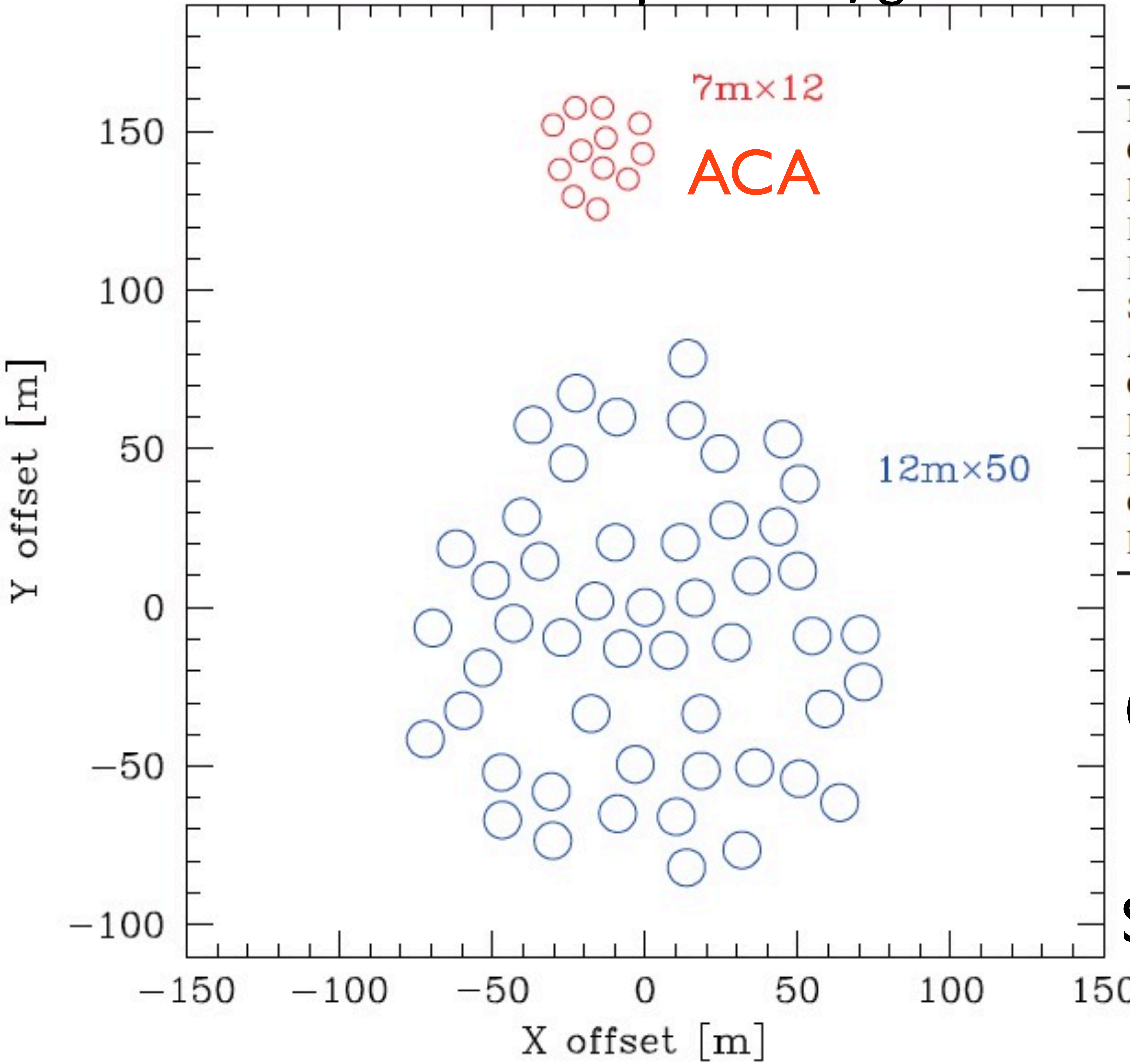


- MUSTANG data, which have a slightly higher angular resolution and a lot more S/N, are totally consistent with our finding.

ALMA

- Can ALMA do the high-resolution mapping of SZ?
  - Yes, for some compact/bright clusters.
  - *Yamada et al., PASJ, 64, 102 (2012)*

ALMA's most compact configuration

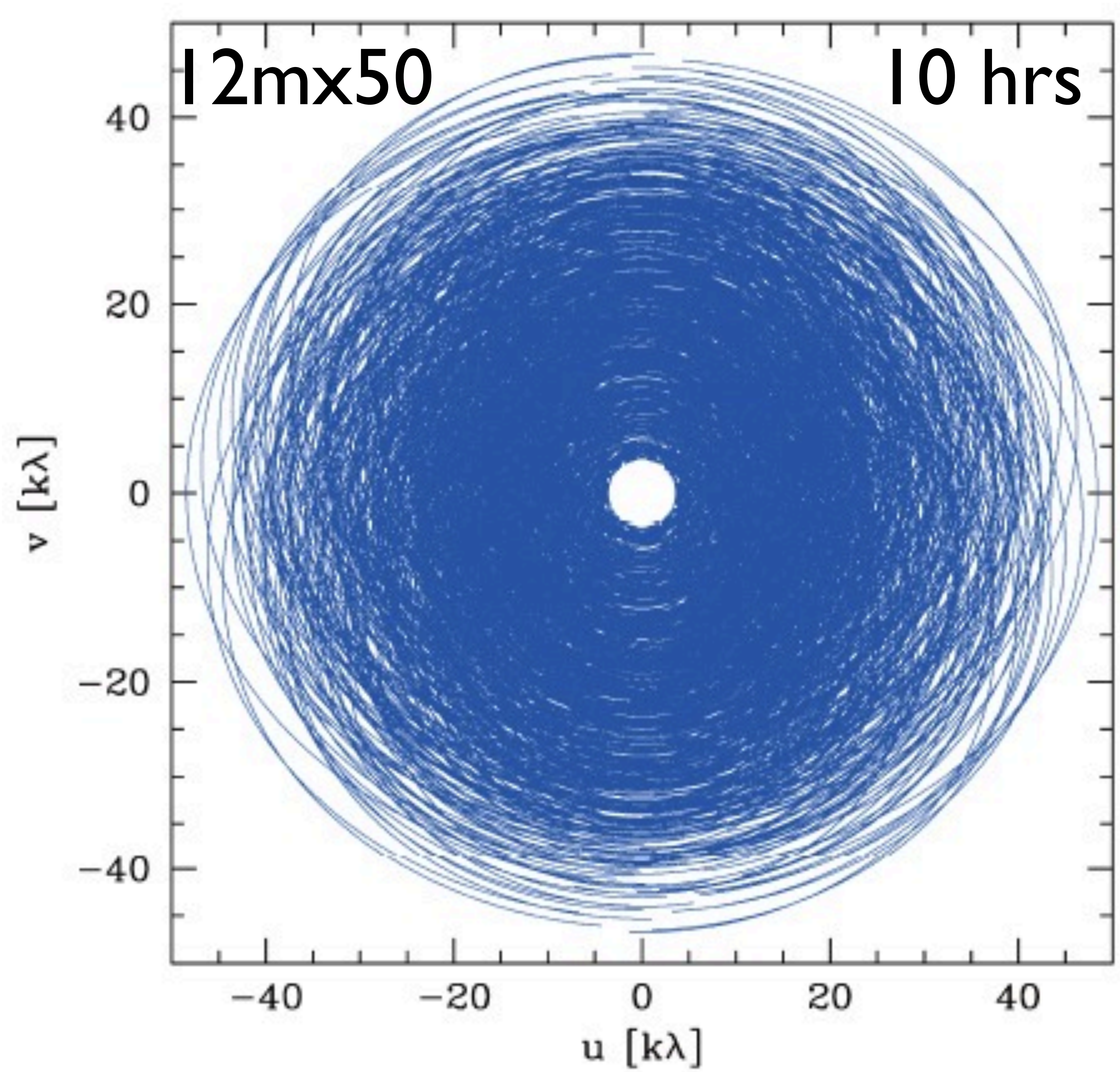


Number of antennas	12 m × 50, 7 m × 12, SD × 4
Configuration	Most compact
Frequency	$\boxed{\text{90 GHz (Band 3)}}$
Bandwidth	7.5 GHz per polarization
Intermediate frequency	6 GHz
System temperature	73.5 K
Aperture efficiency	0.71
Correlator efficiency	0.88
Primary beam FWHM	69″ (12 m × 50), 118″ (7 m × 12)
Phase error (rms)	20°
Gain error (rms)	0.1%
Pointing error (rms)	0.″6

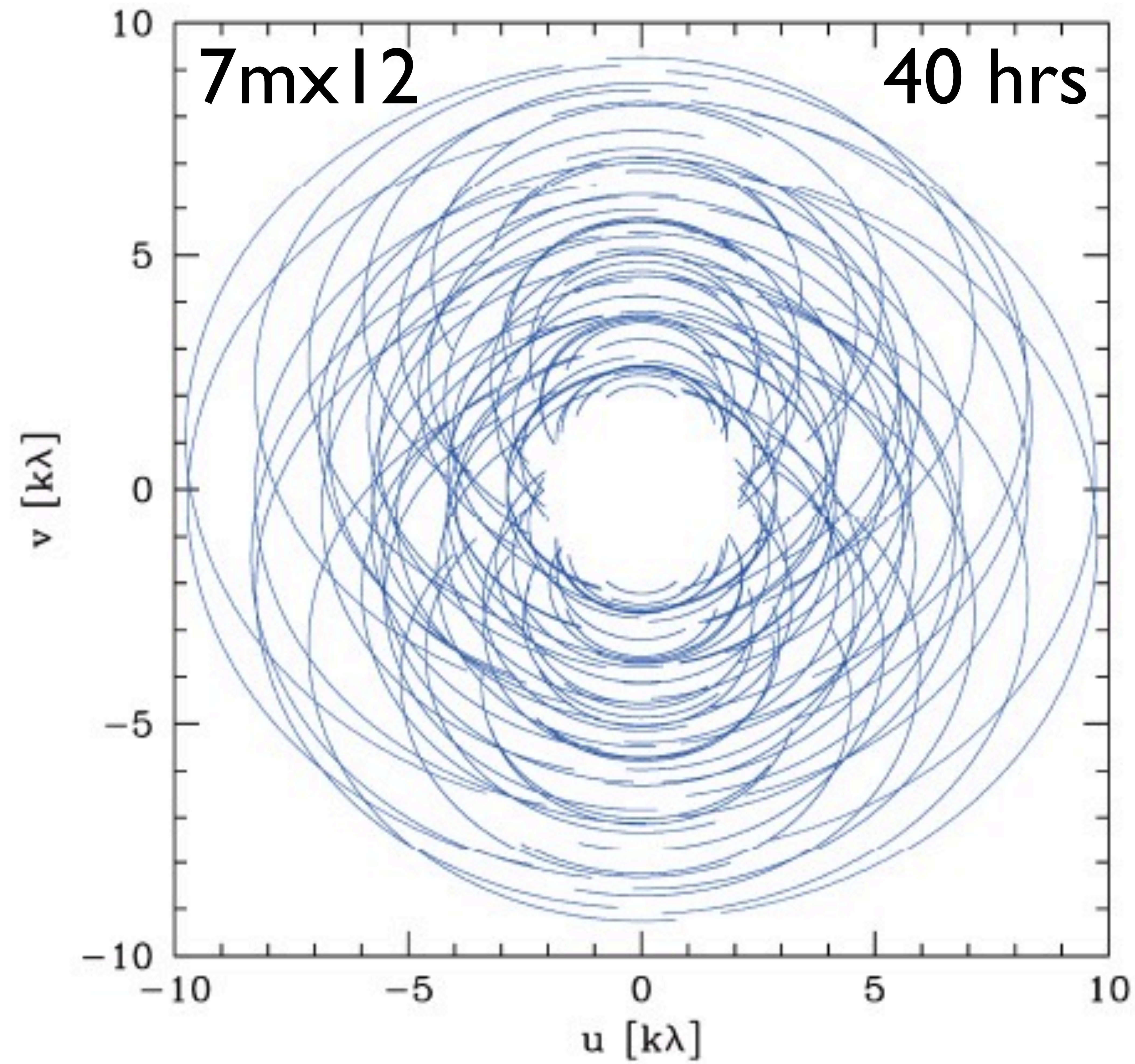
Atacama Compact Array (ACA) would be crucial for SZ observations with ALMA.

Synthesized beam FWHM ~ 5"

u-v coverage (toward Bullet)

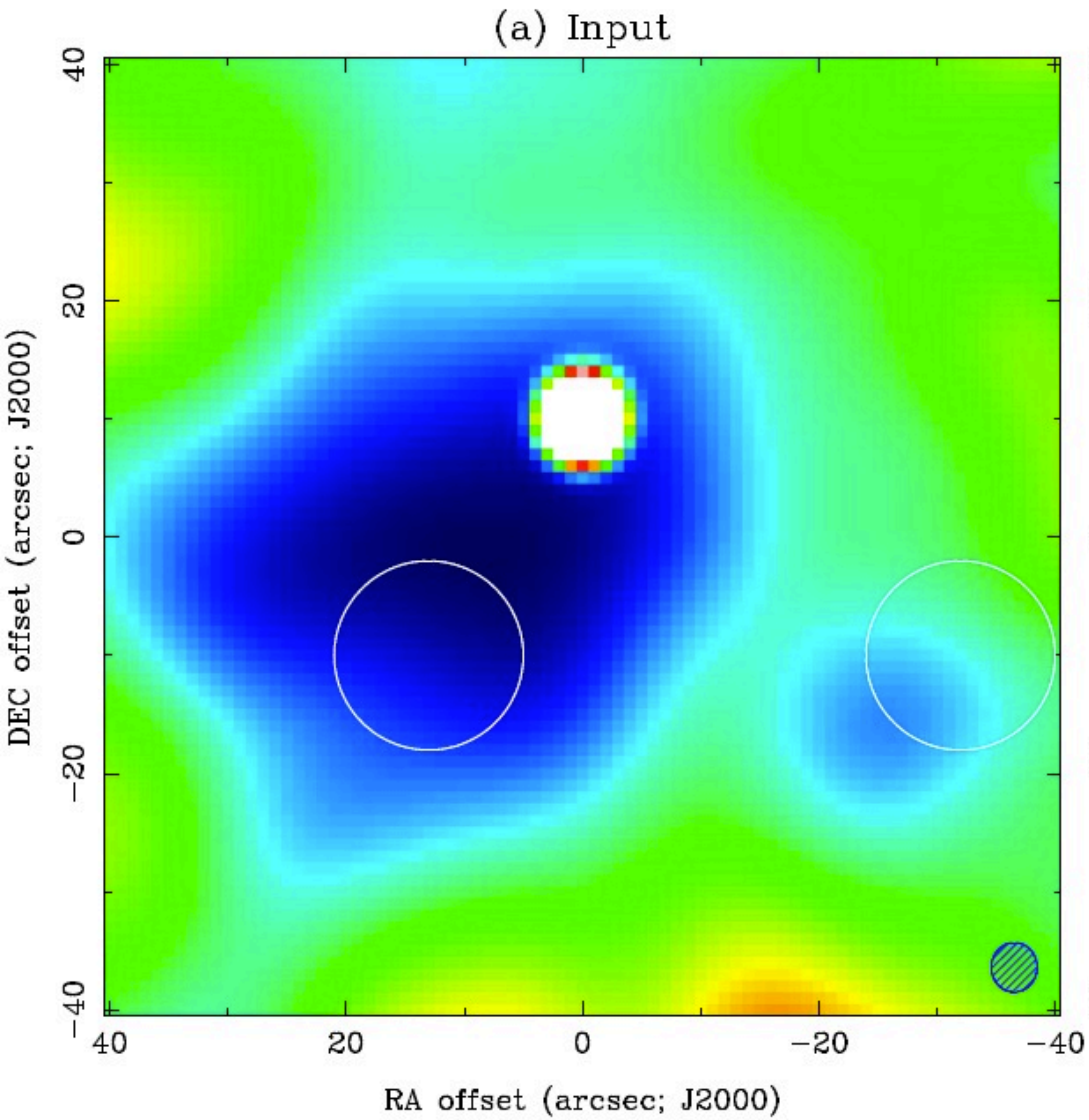


4–48 kλ uniformly covered

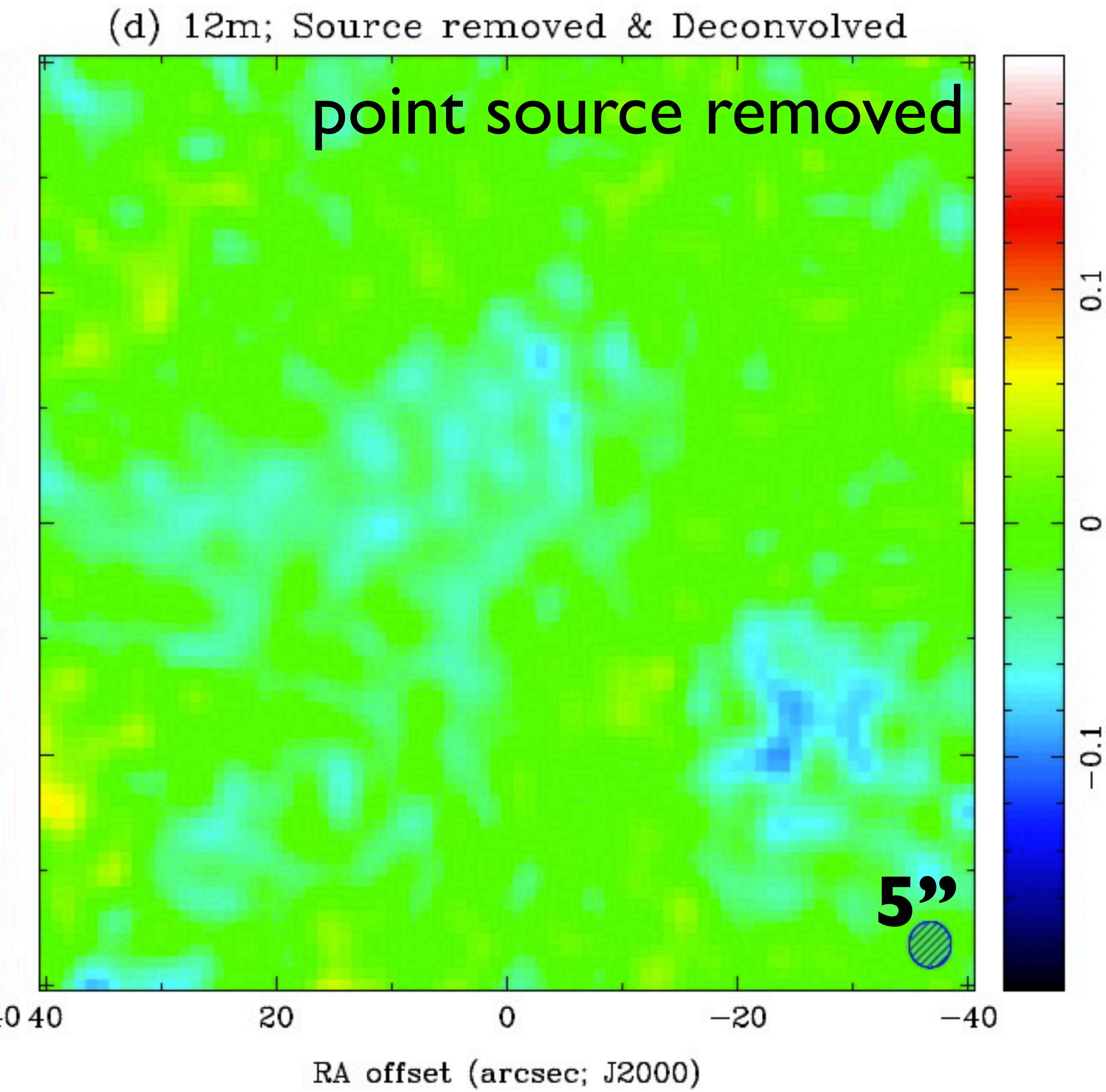


2–10 kλ uniformly covered

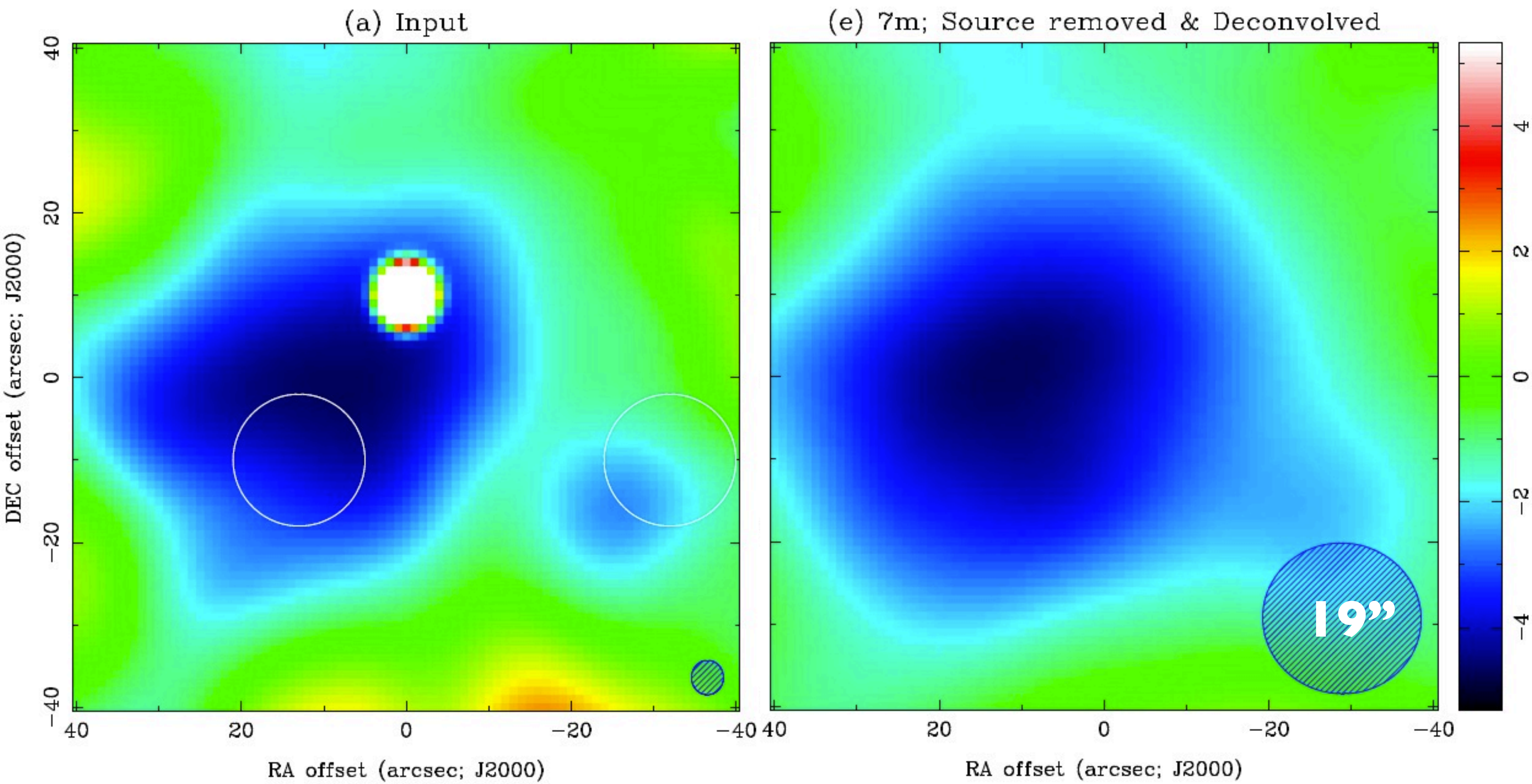
Case I: RXJ1347–1145



Input SZ image from a smoothed SZ map of RXJ1347-1145

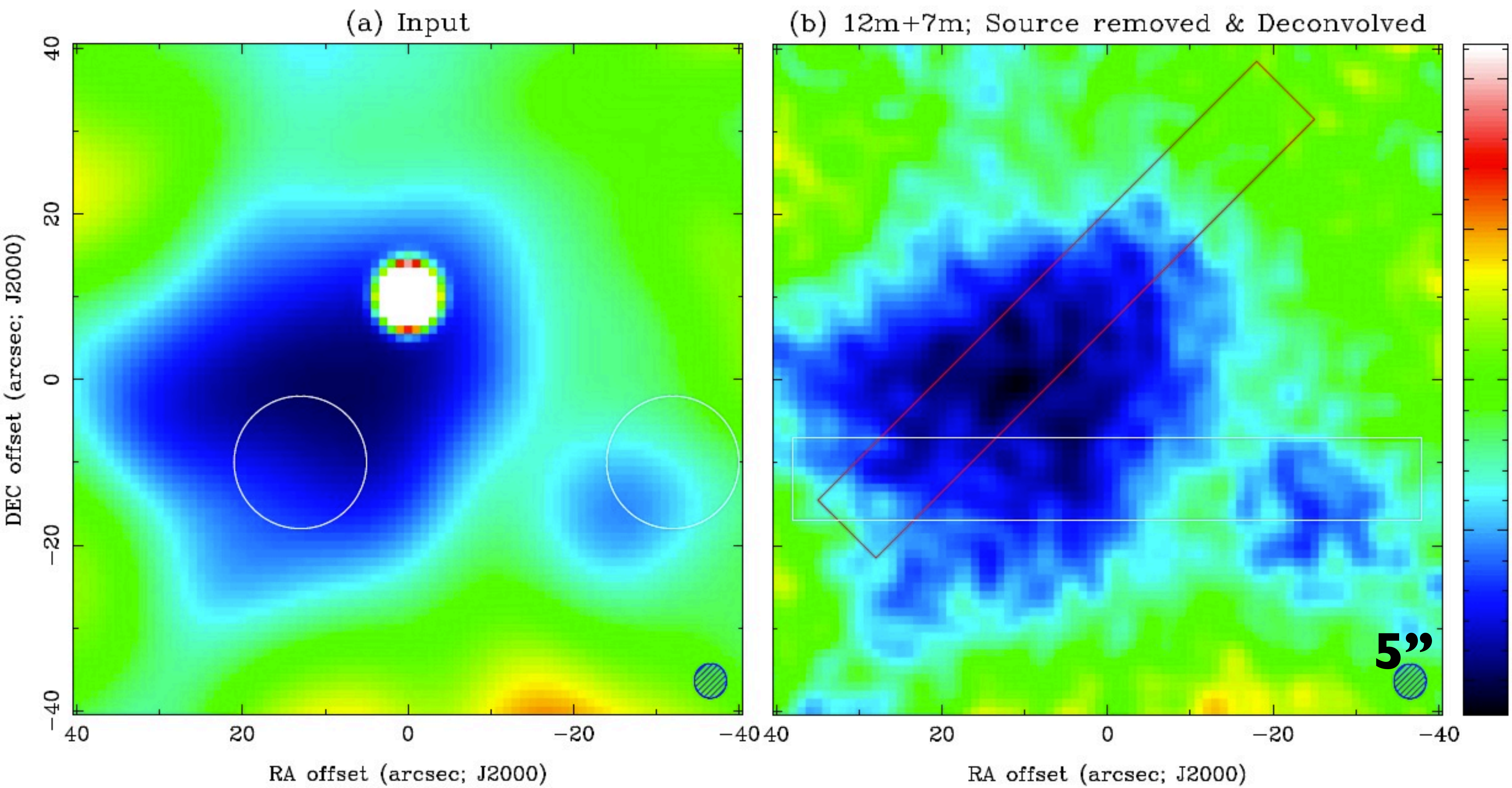


12mx50 only



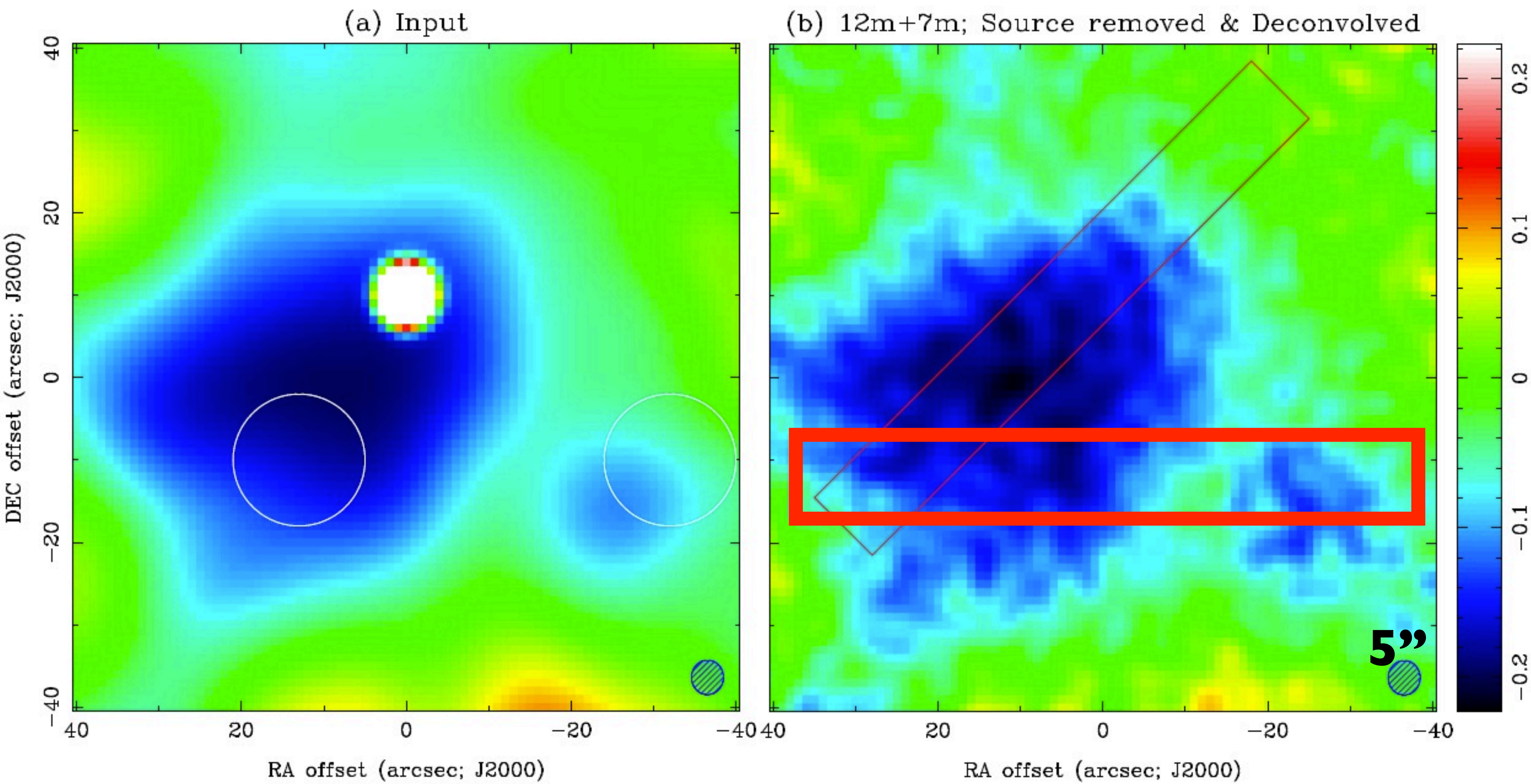
Input SZ image from a smoothed SZ map of RXJ1347-1145

7mx12 only



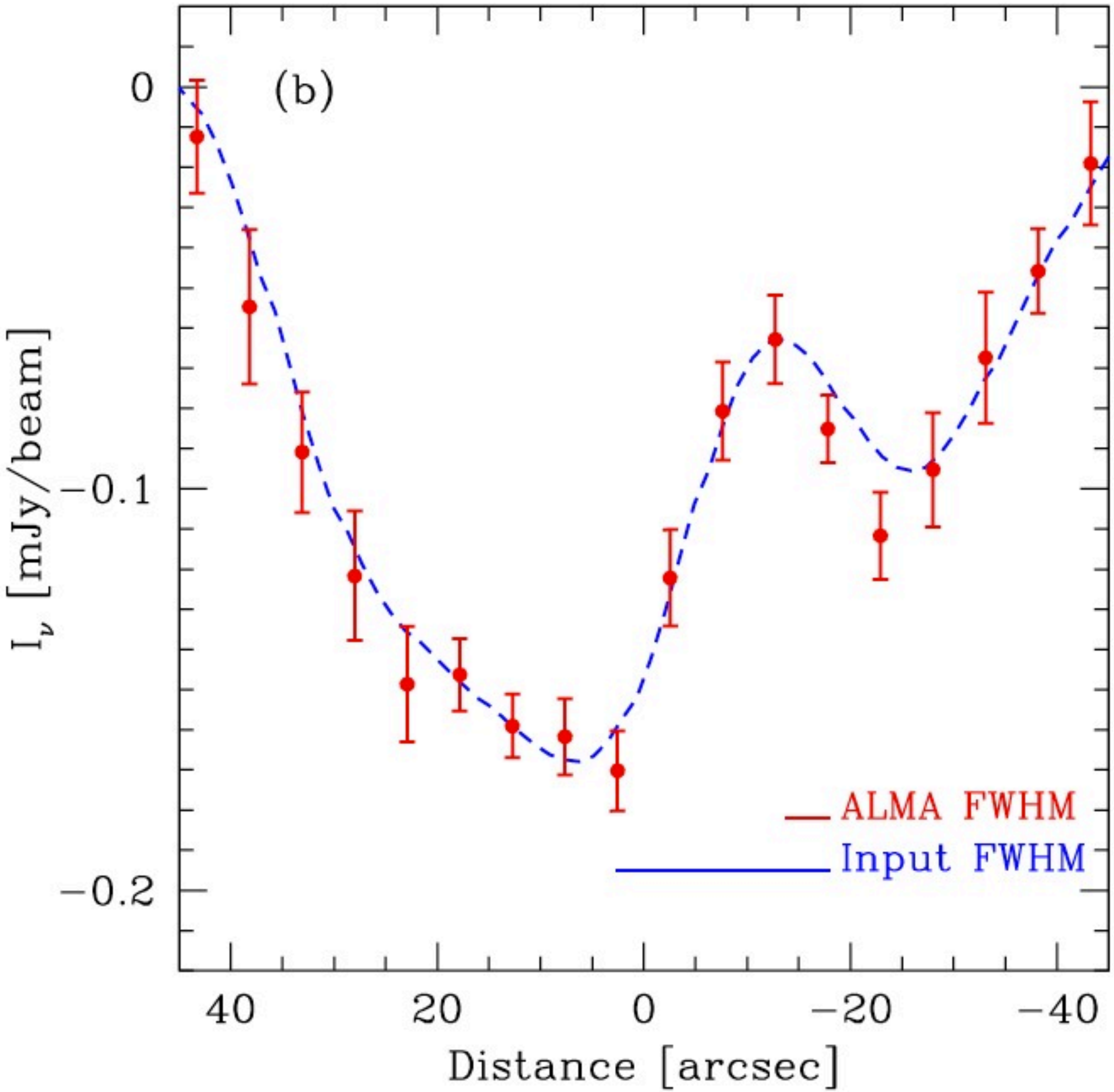
Input SZ image from a smoothed SZ map of RXJ1347-1145

Combined



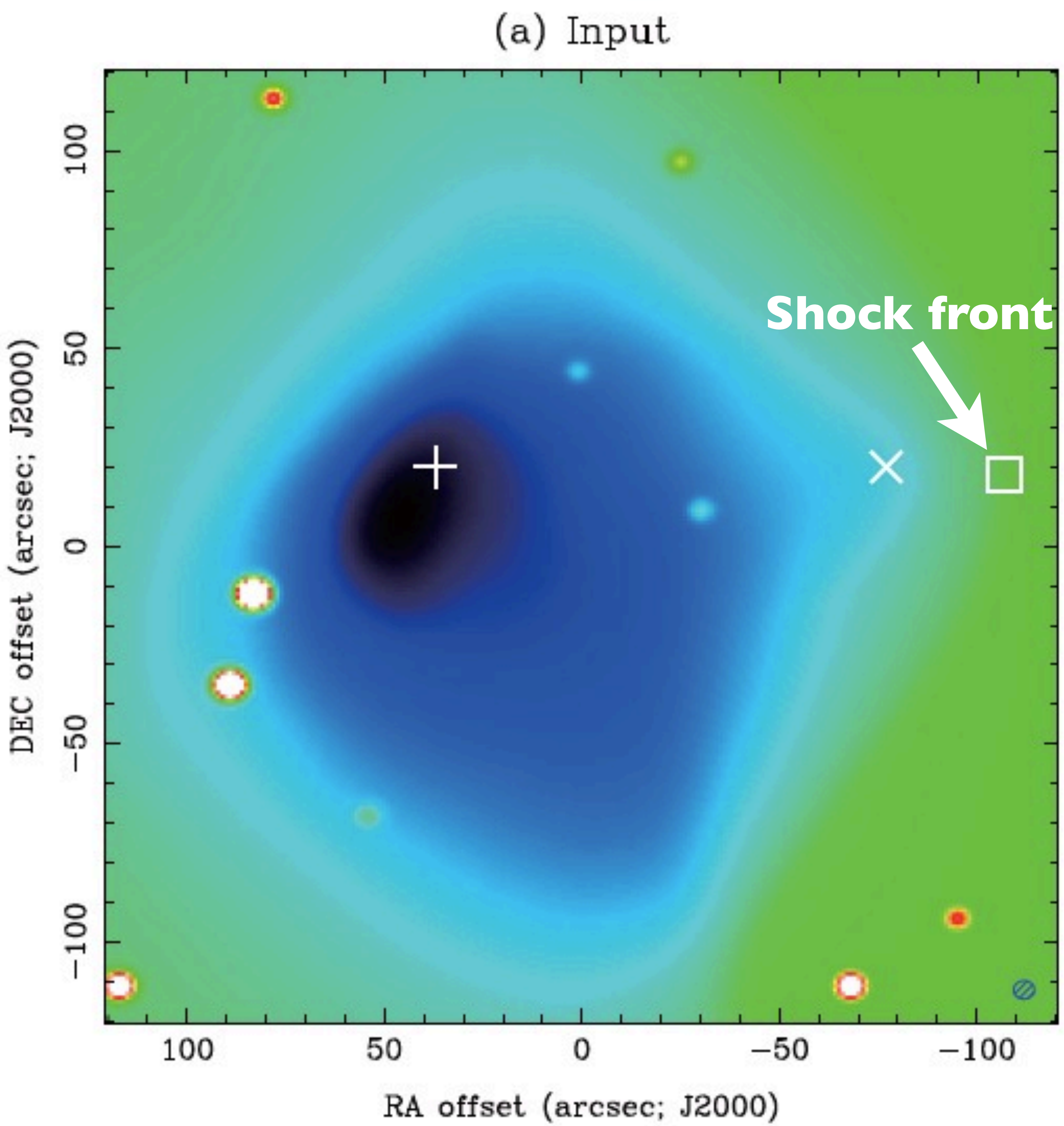
Input SZ image from a smoothed SZ map of RXJ1347-1145

Combined

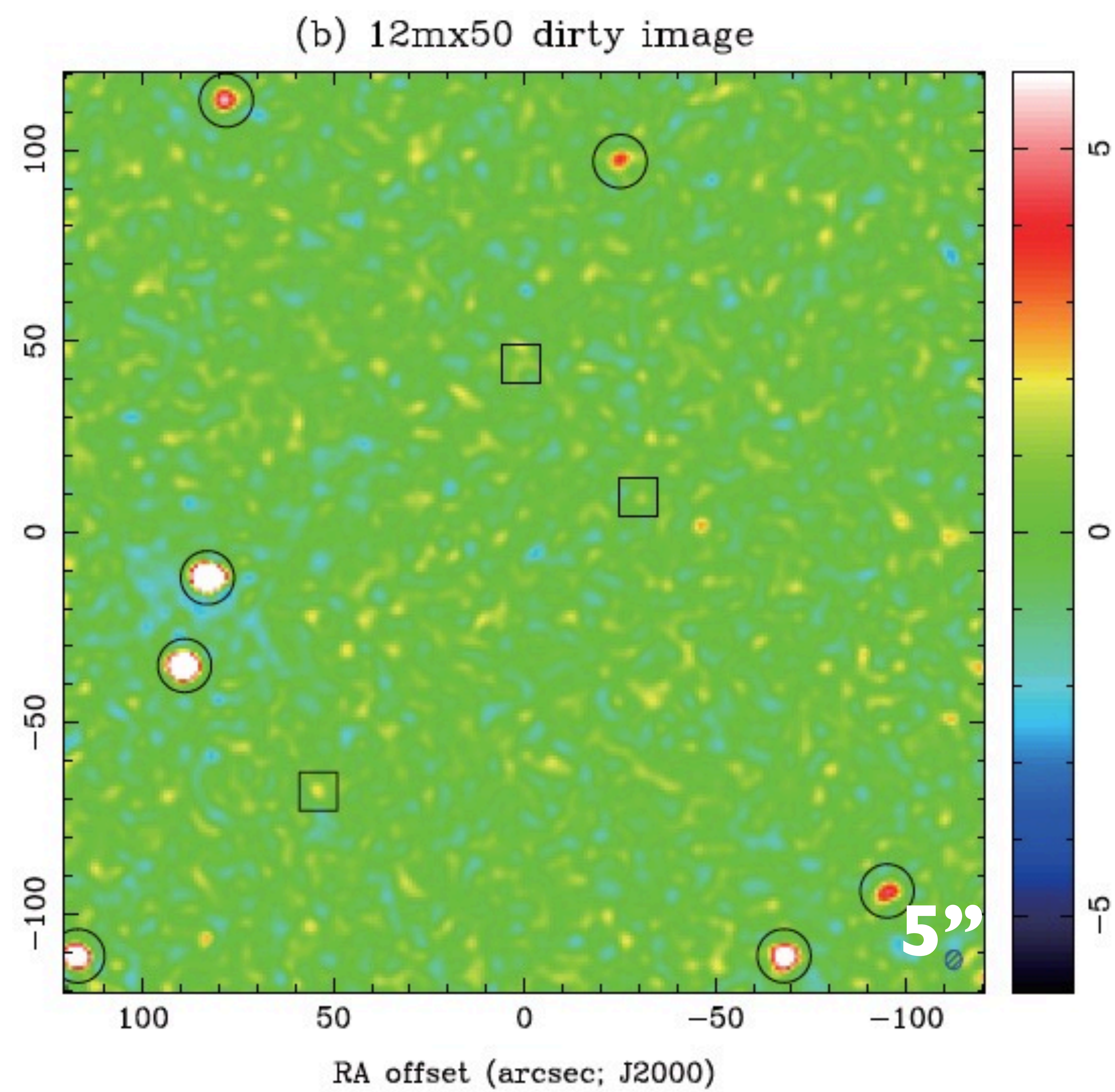


- Good recovery of the input profile!

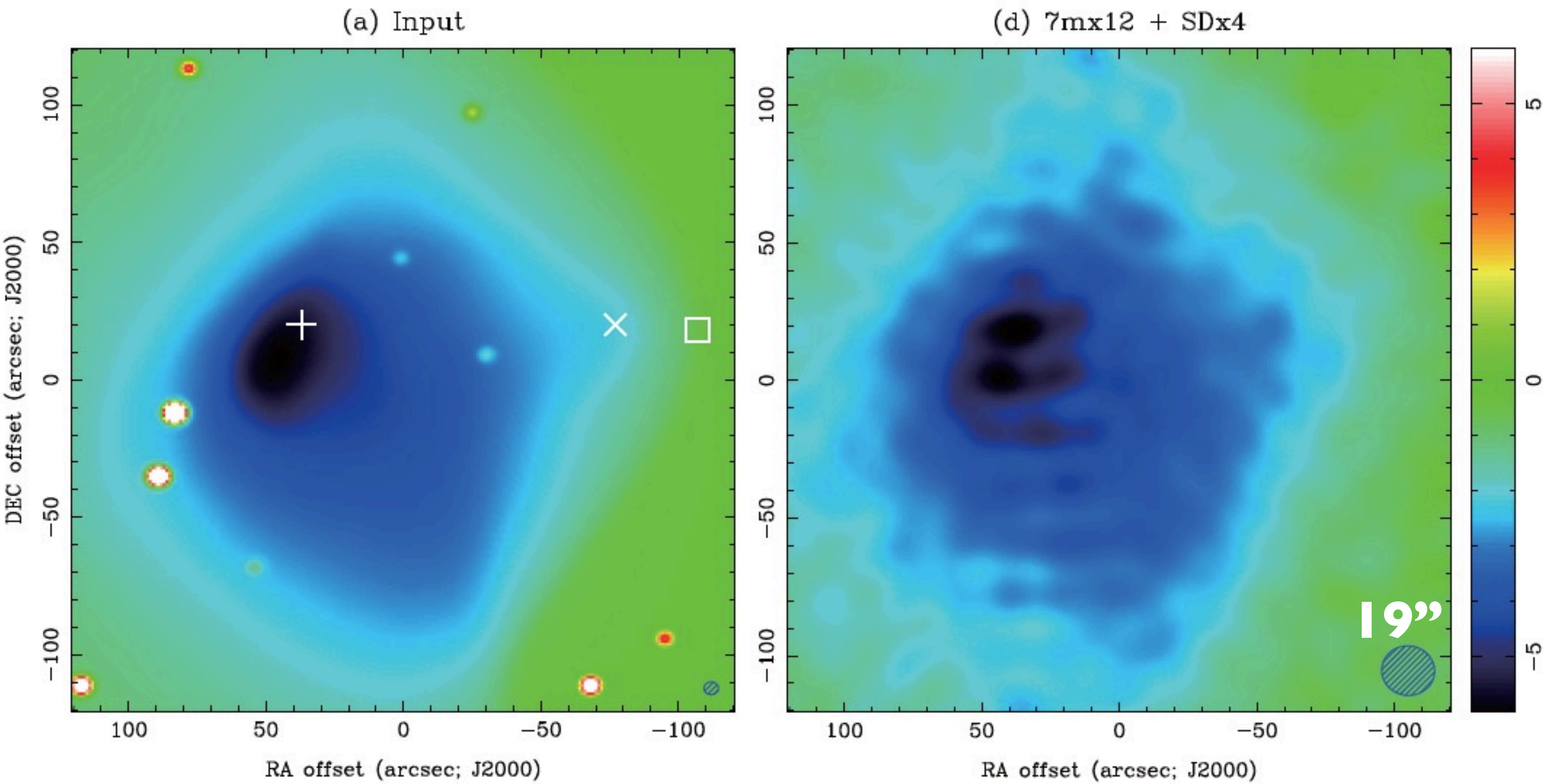
Case II: Bullet Cluster



Input SZ image from the SPH Simulation of Bullet by Akahori&Yoshikawa(2012)

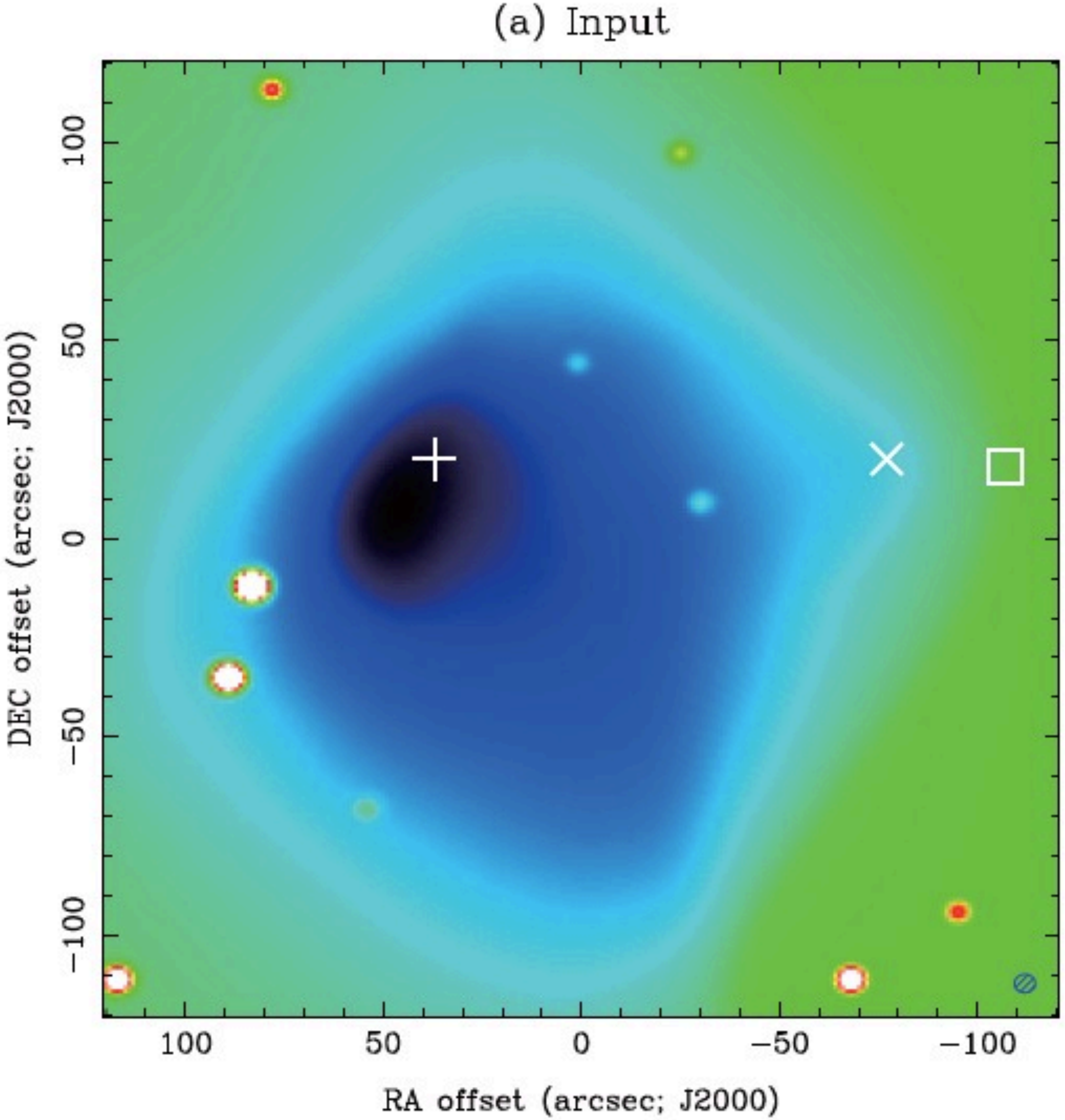


12mx50 only

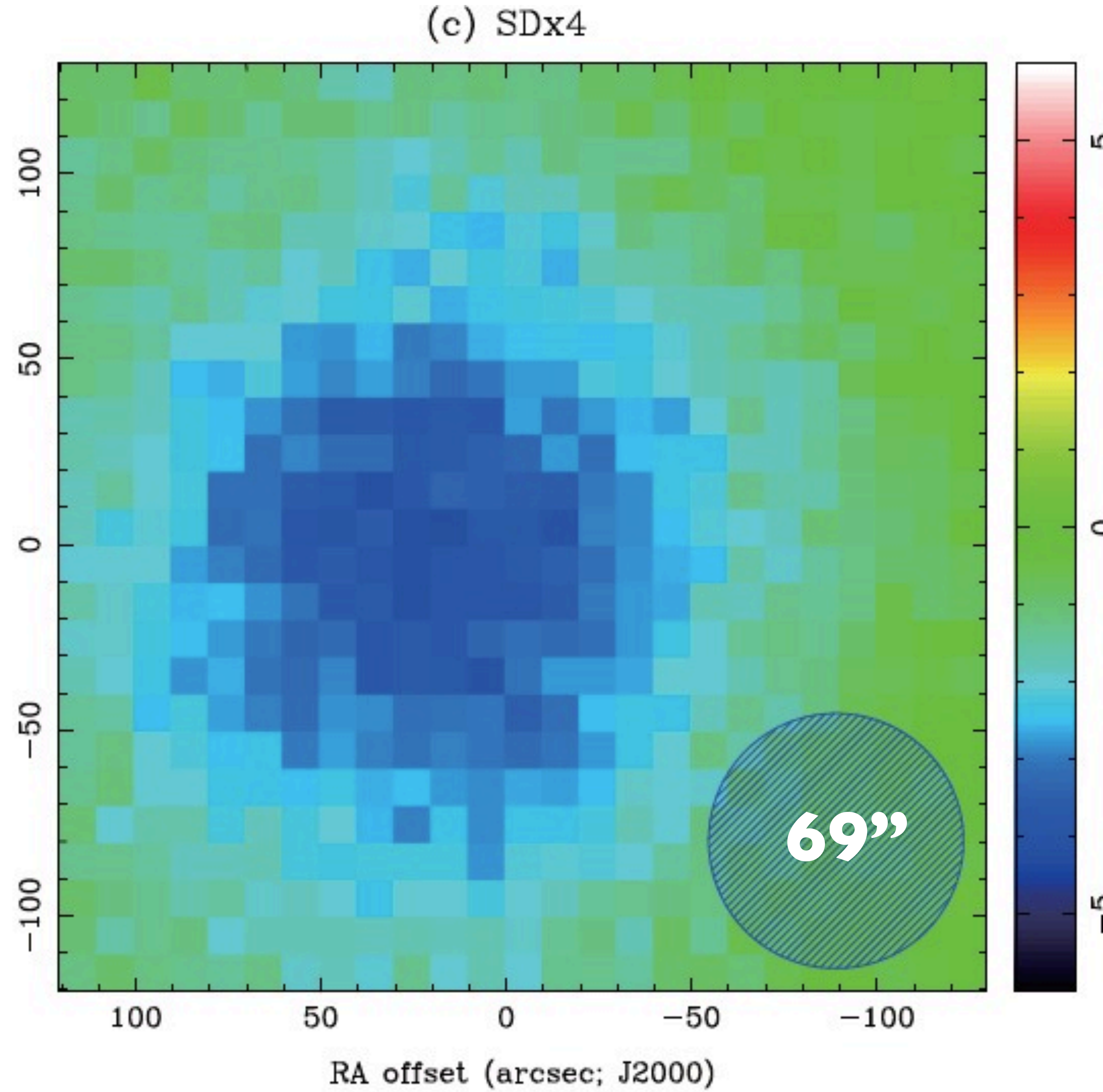


Input SZ image from the SPH Simulation of Bullet by Akahori&Yoshikawa(2012)

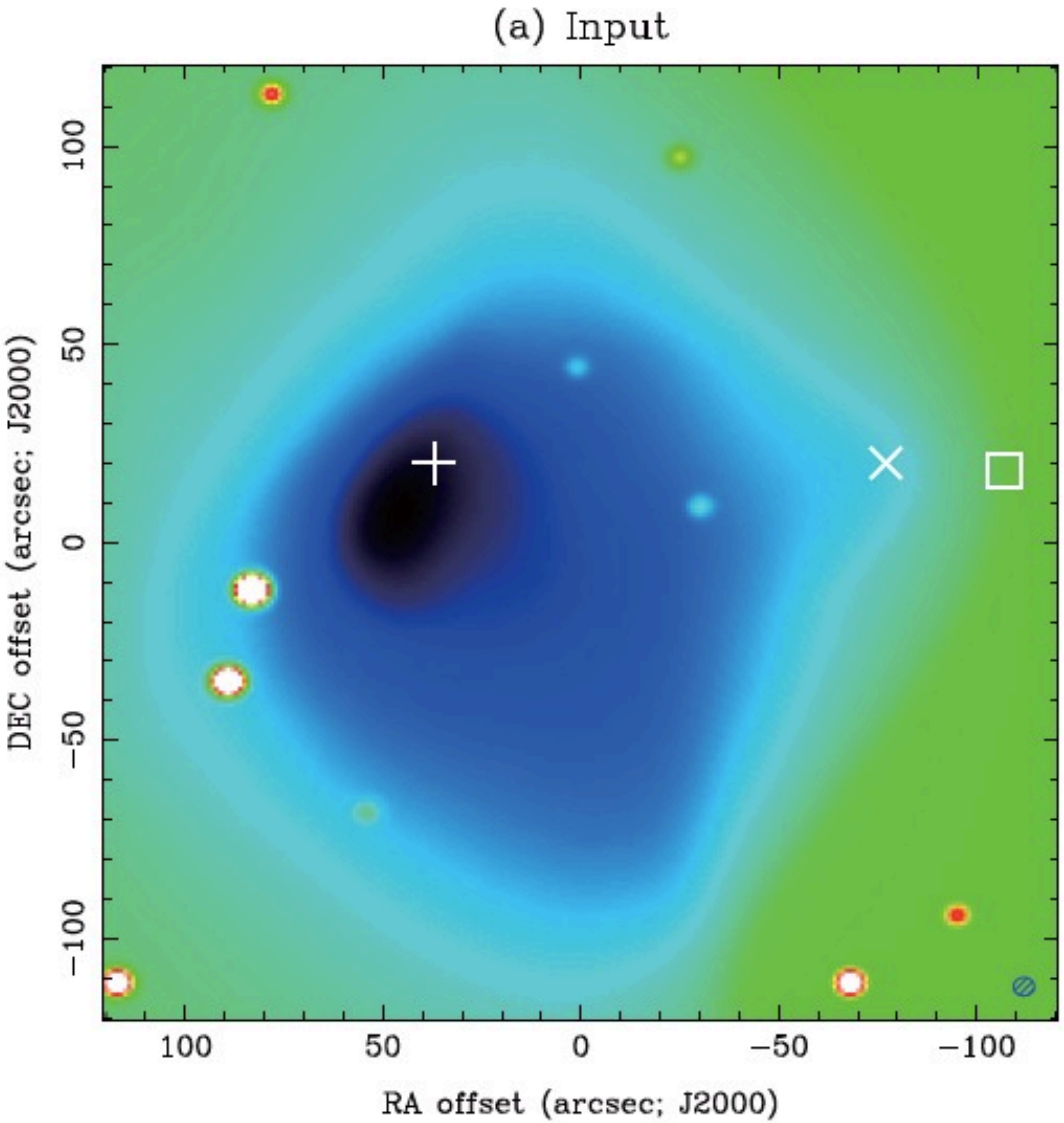
7mx12 [+12m SDx4]

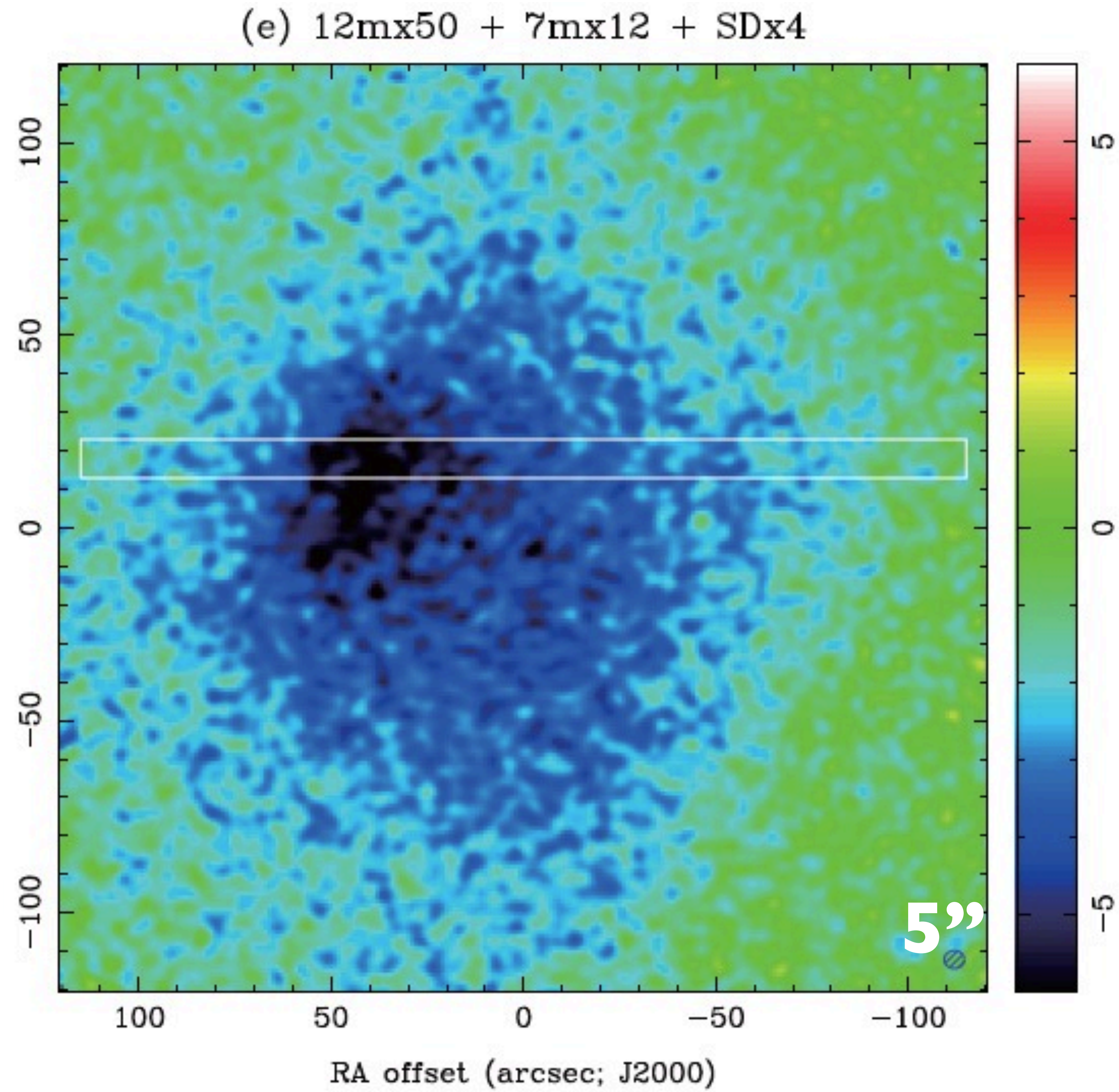


Input SZ image from the SPH Simulation of Bullet by Akahori&Yoshikawa(2012)



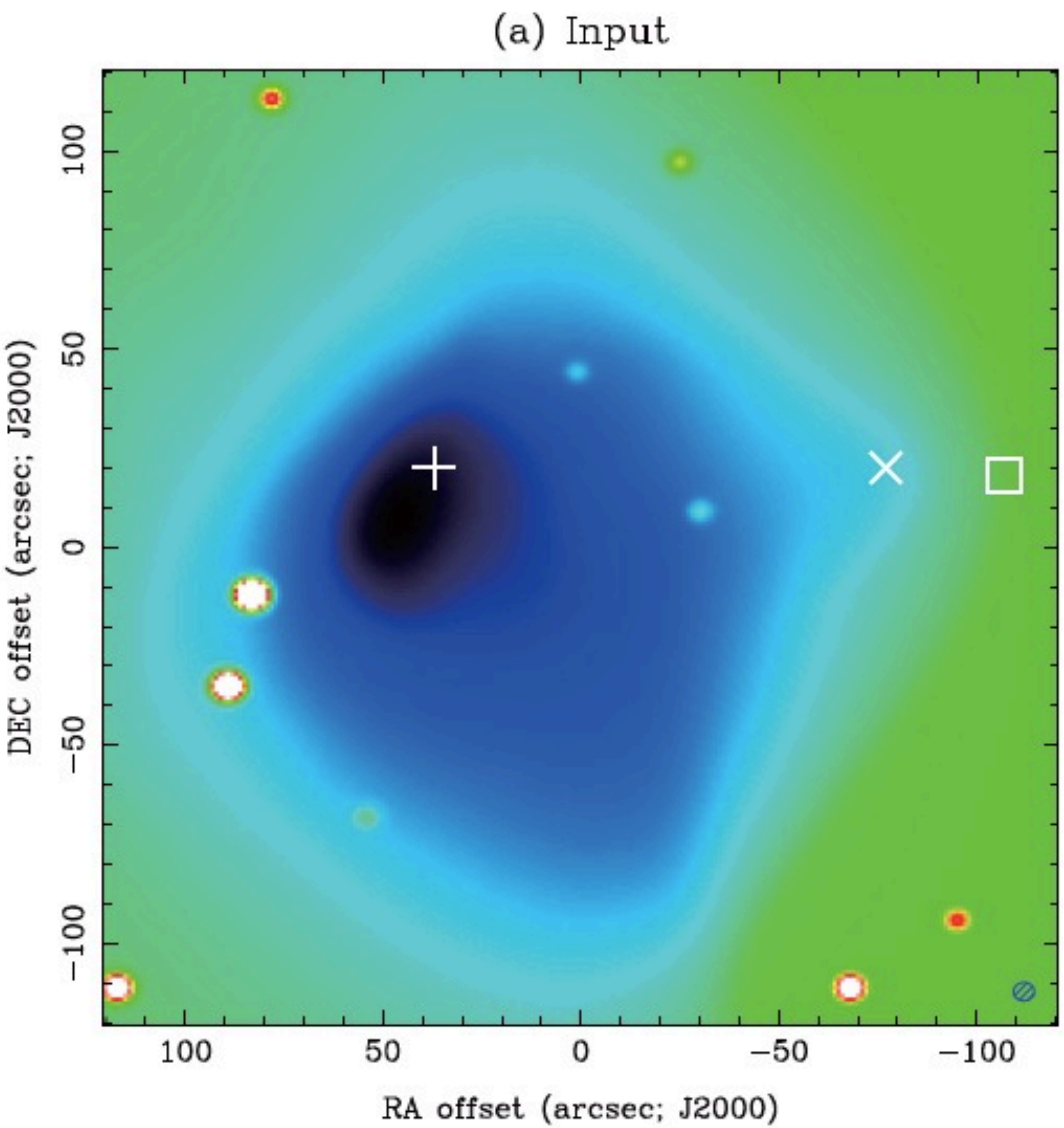
12m SDx4 Only
(to get the baseline)



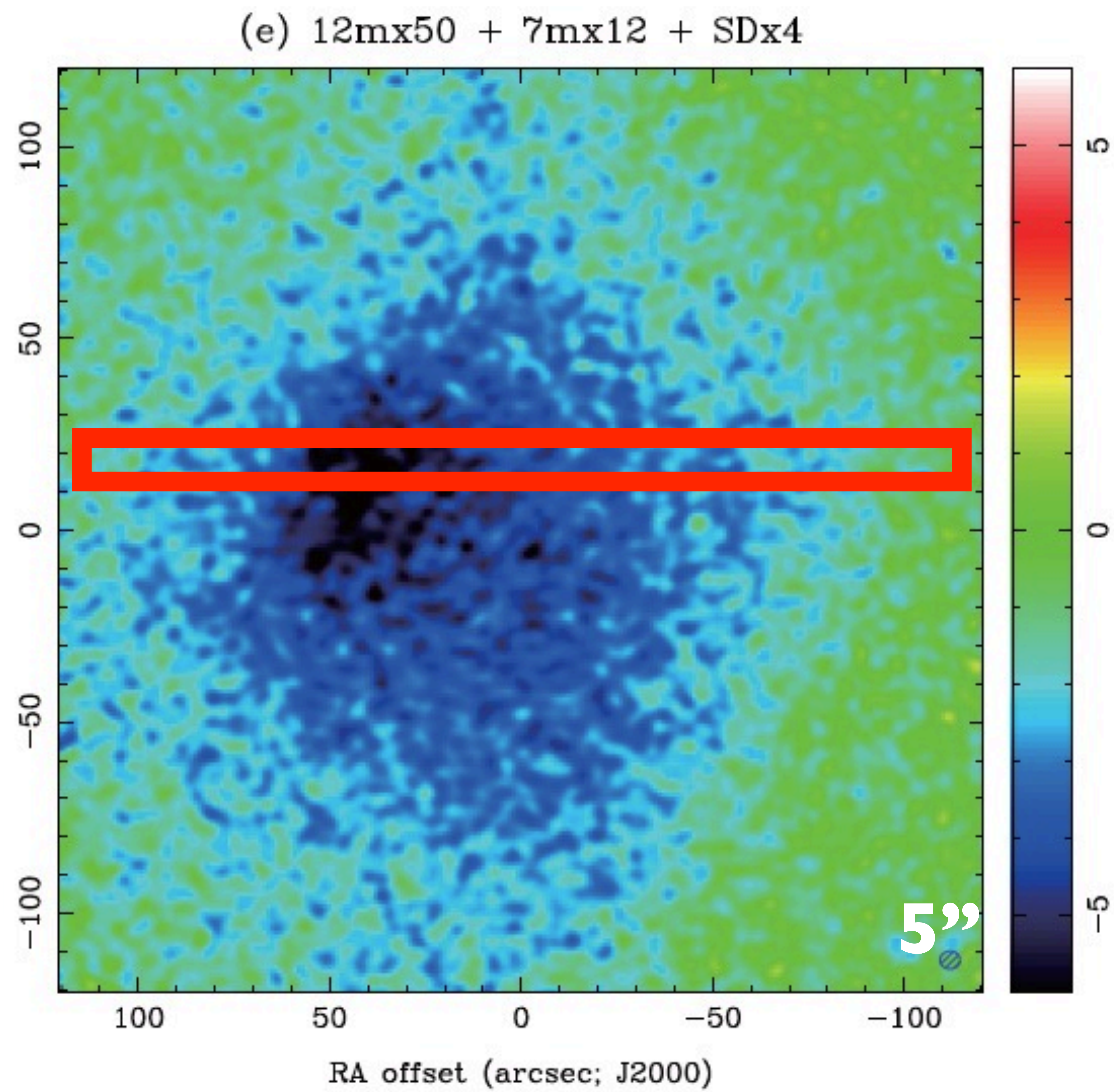


Input SZ image from the SPH Simulation of Bullet by Akahori&Yoshikawa(2012)

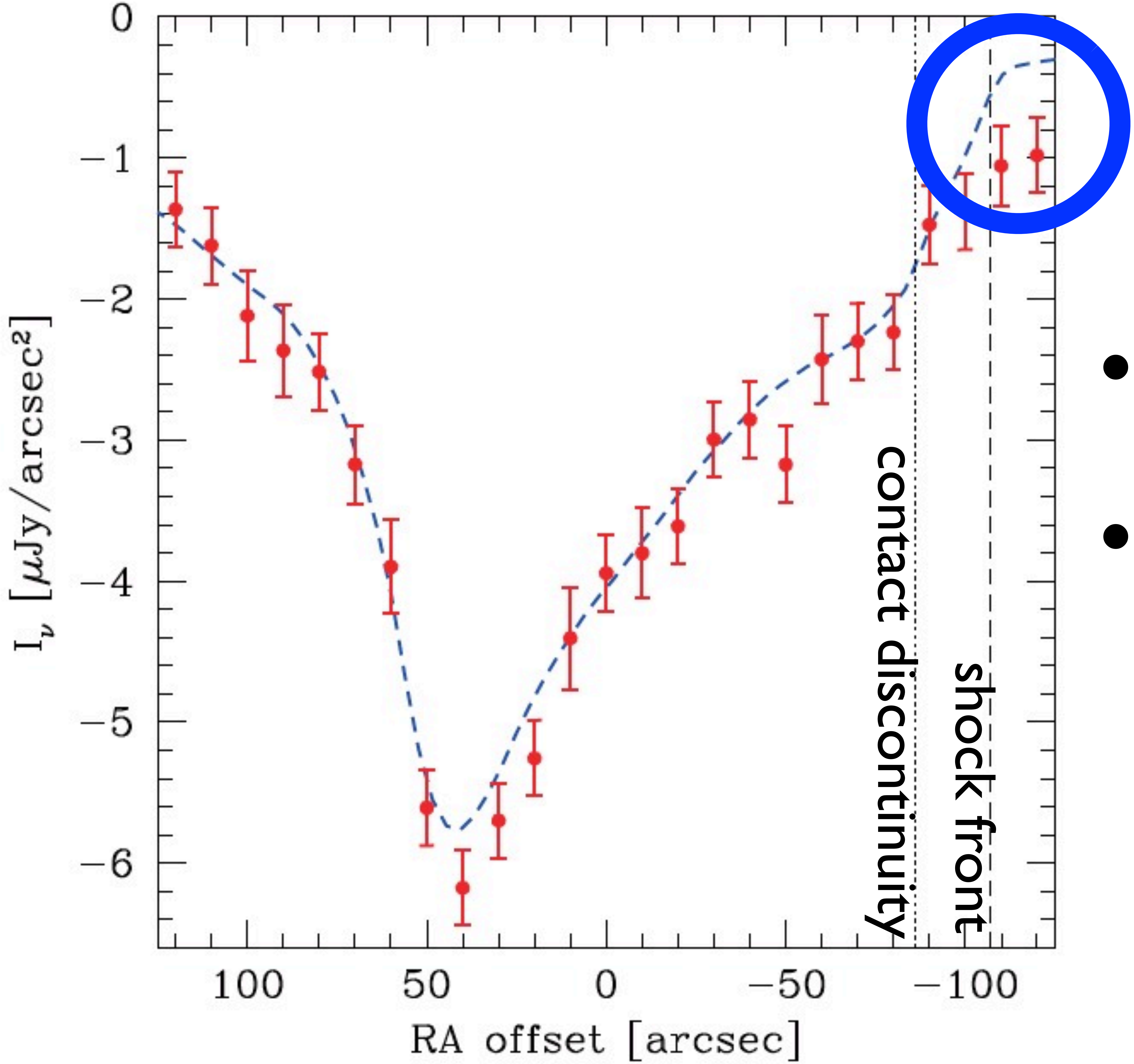
All combined



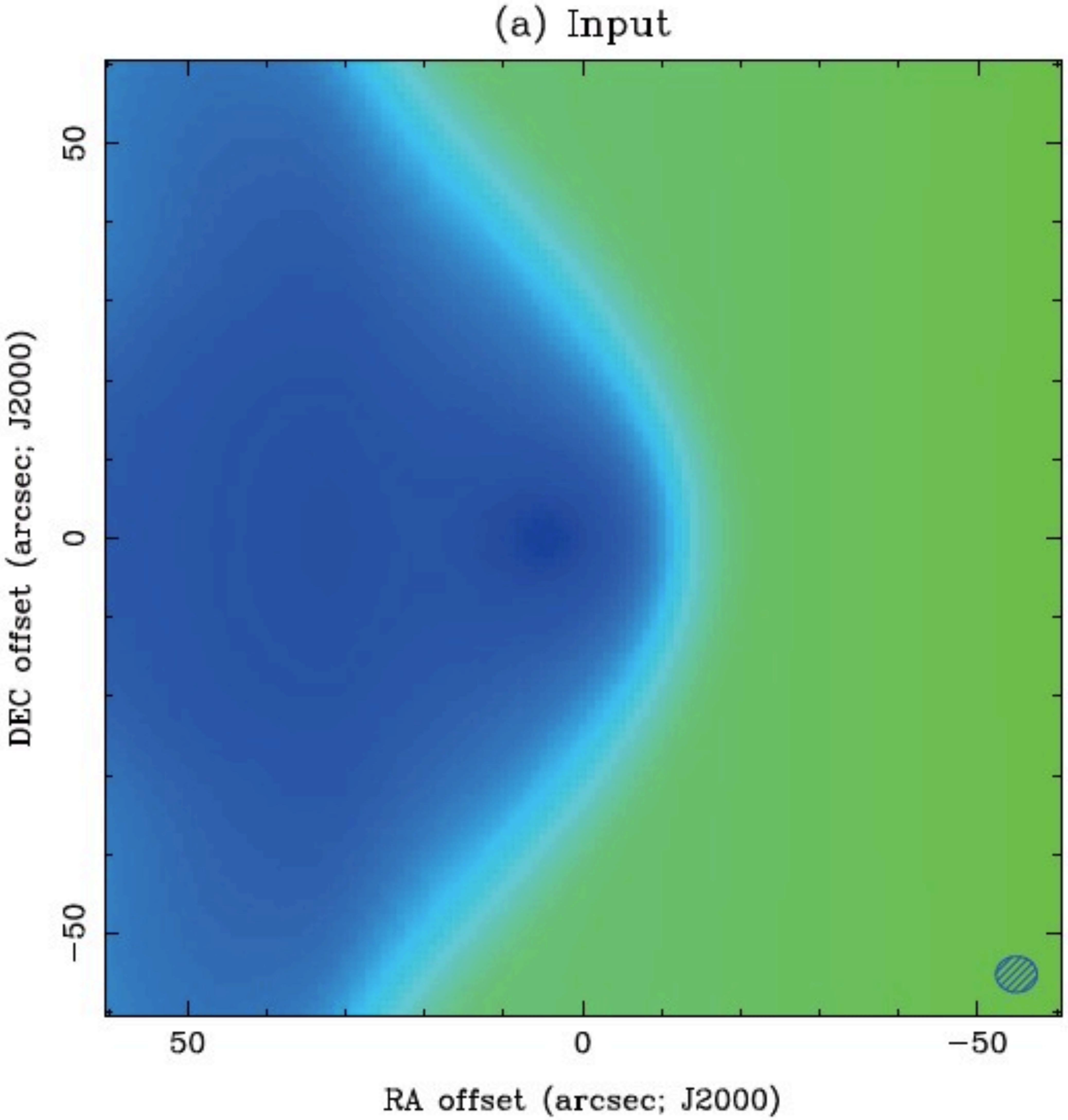
Input SZ image from the SPH Simulation of Bullet by Akahori&Yoshikawa(2012)

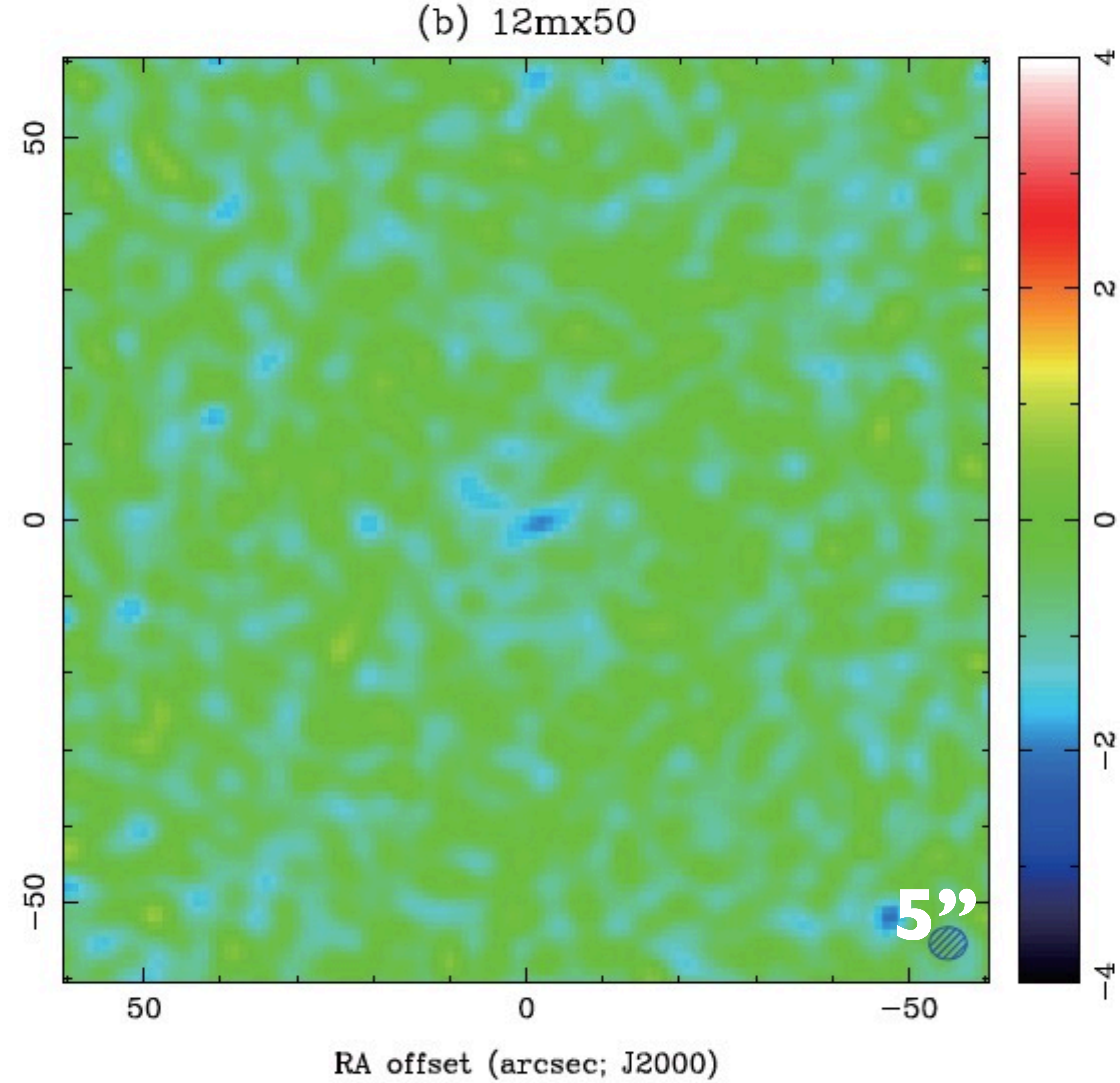


All combined



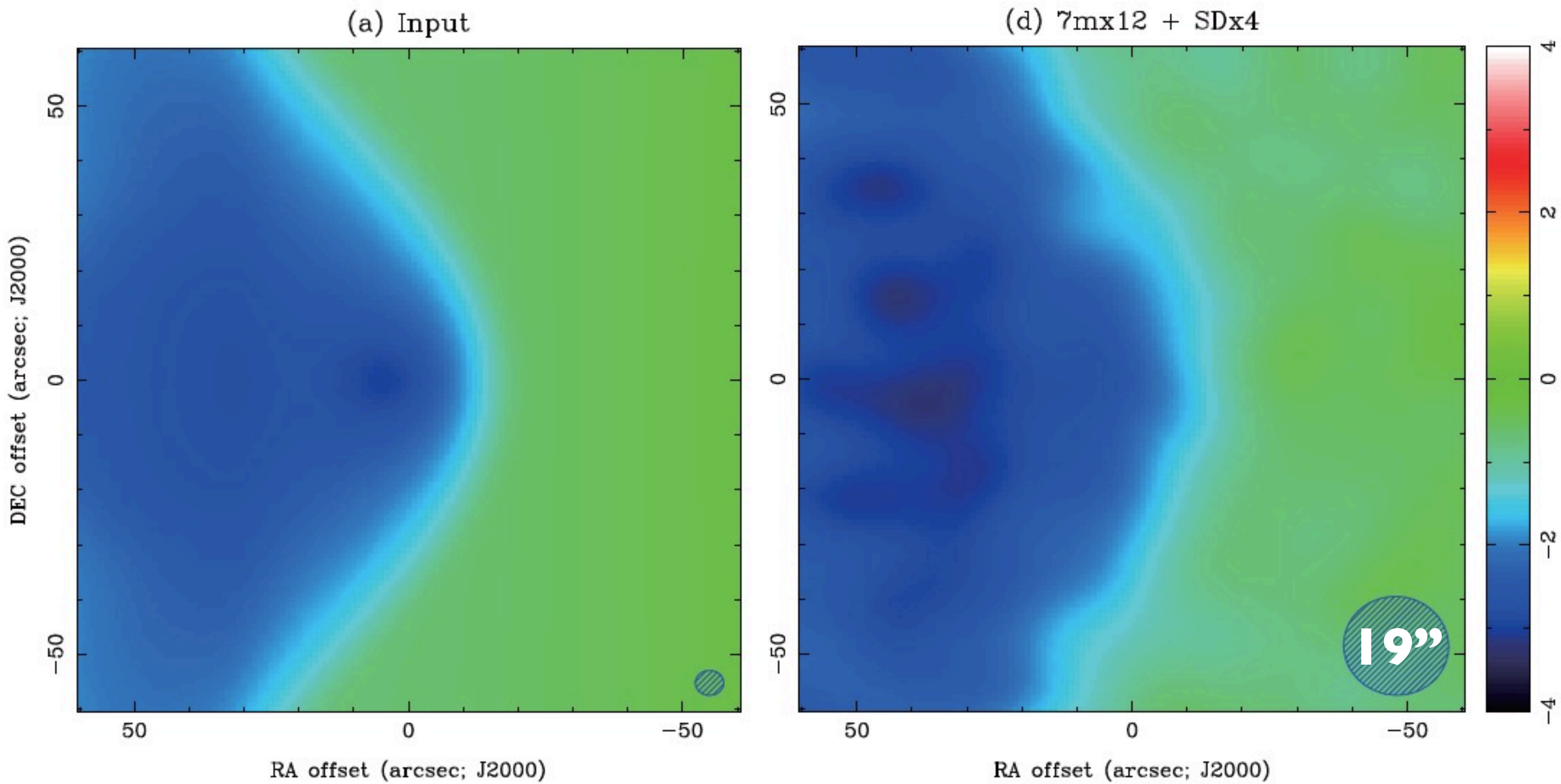
- Good recovery of the global profile
- But, the **shock** is not captured





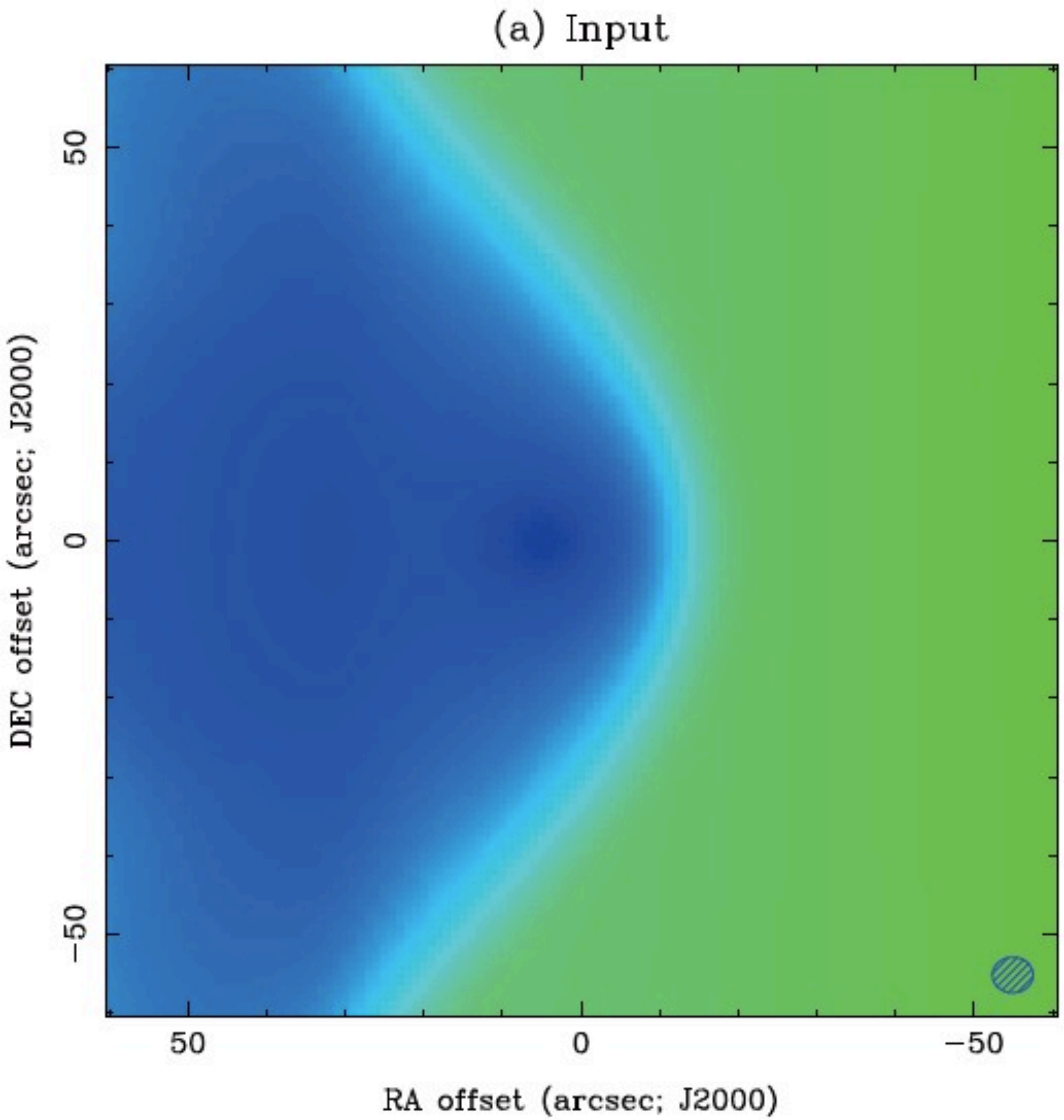
Input SZ image from the Eulerian Simulation of a shock by Takizawa(2005)

12mx50 only

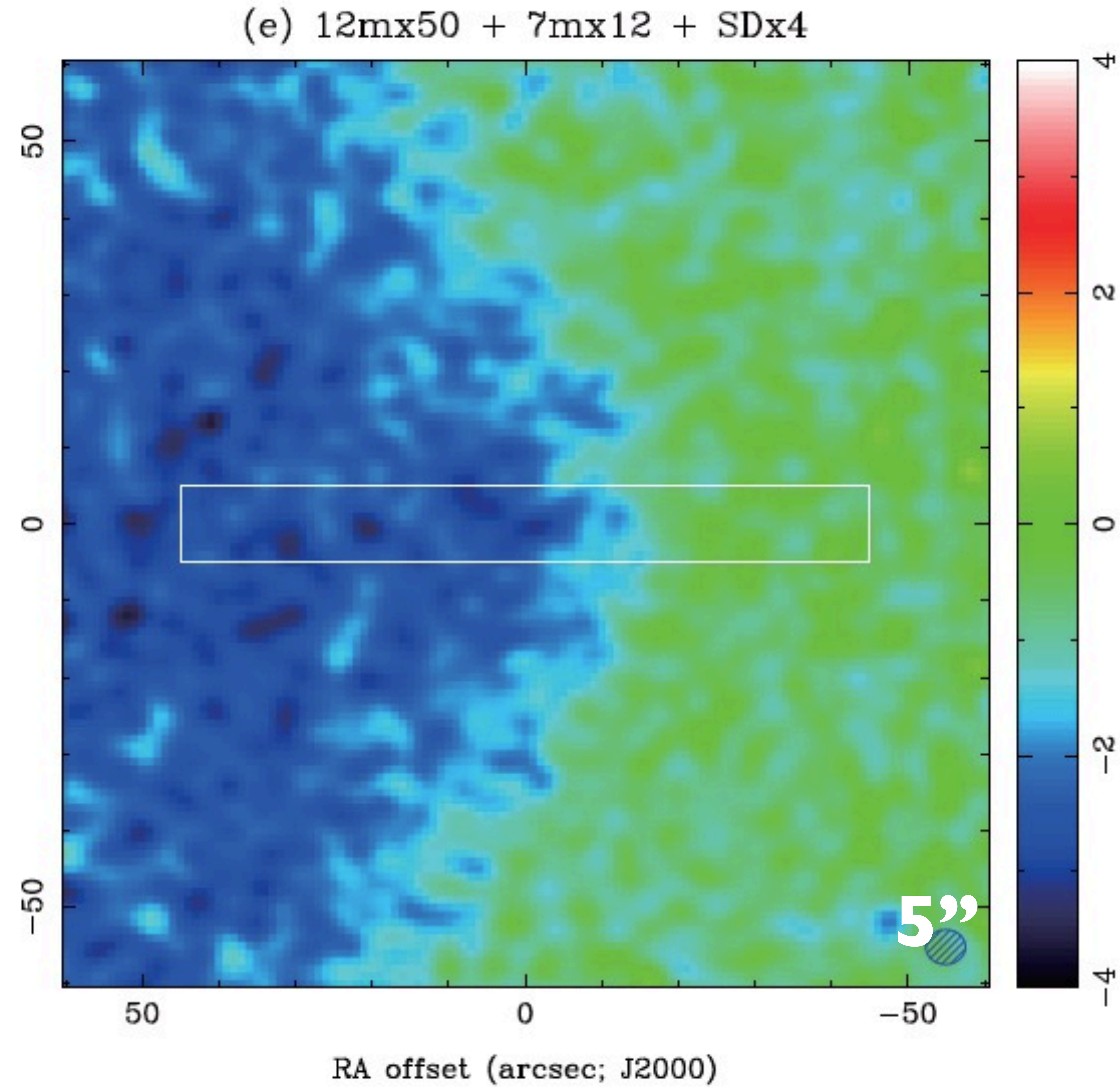


Input SZ image from the Eulerian Simulation of a shock by Takizawa(2005)

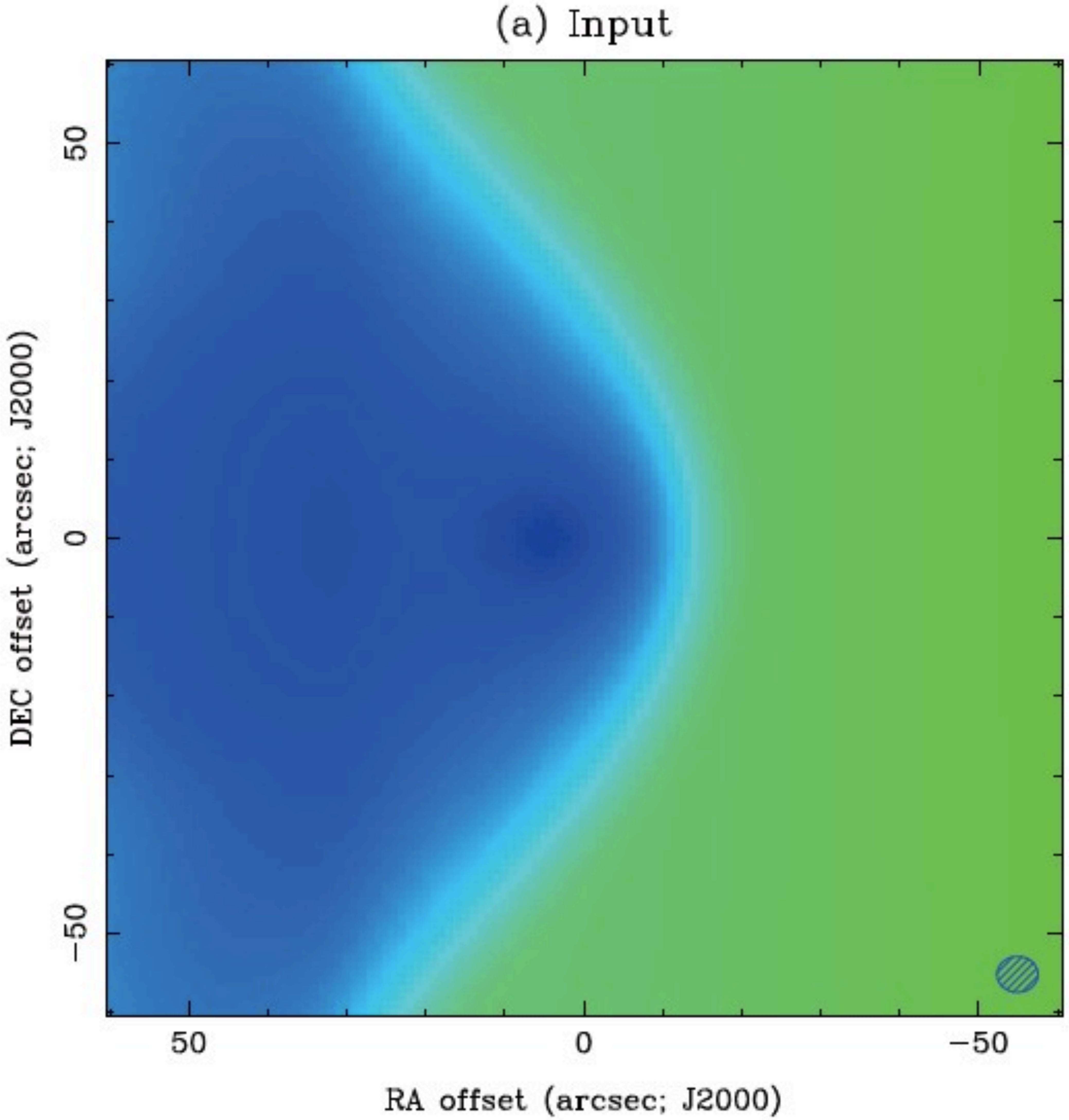
7mx12 [+12m SDx4]



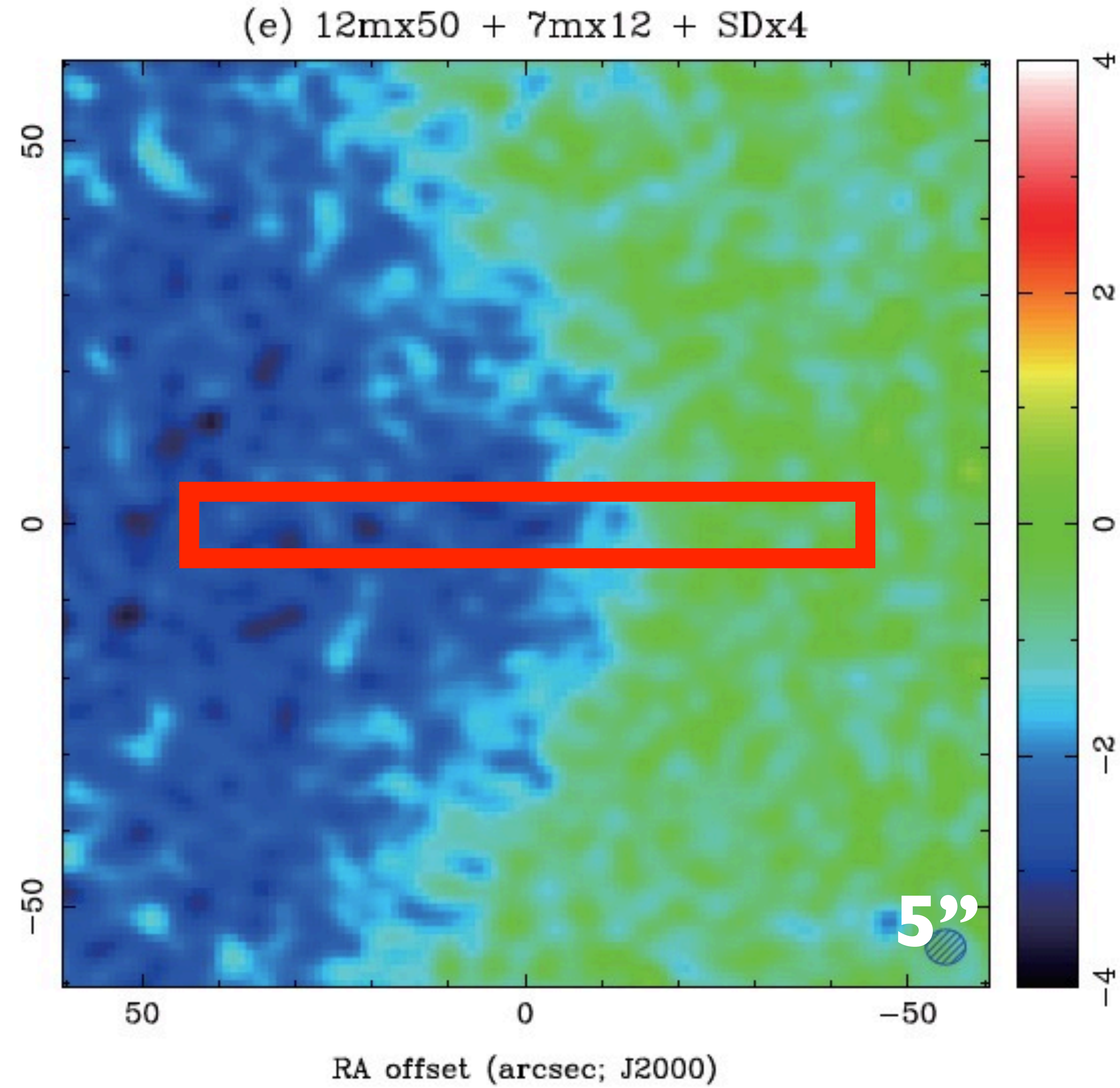
Input SZ image from the Eulerian Simulation of a shock by Takizawa(2005)



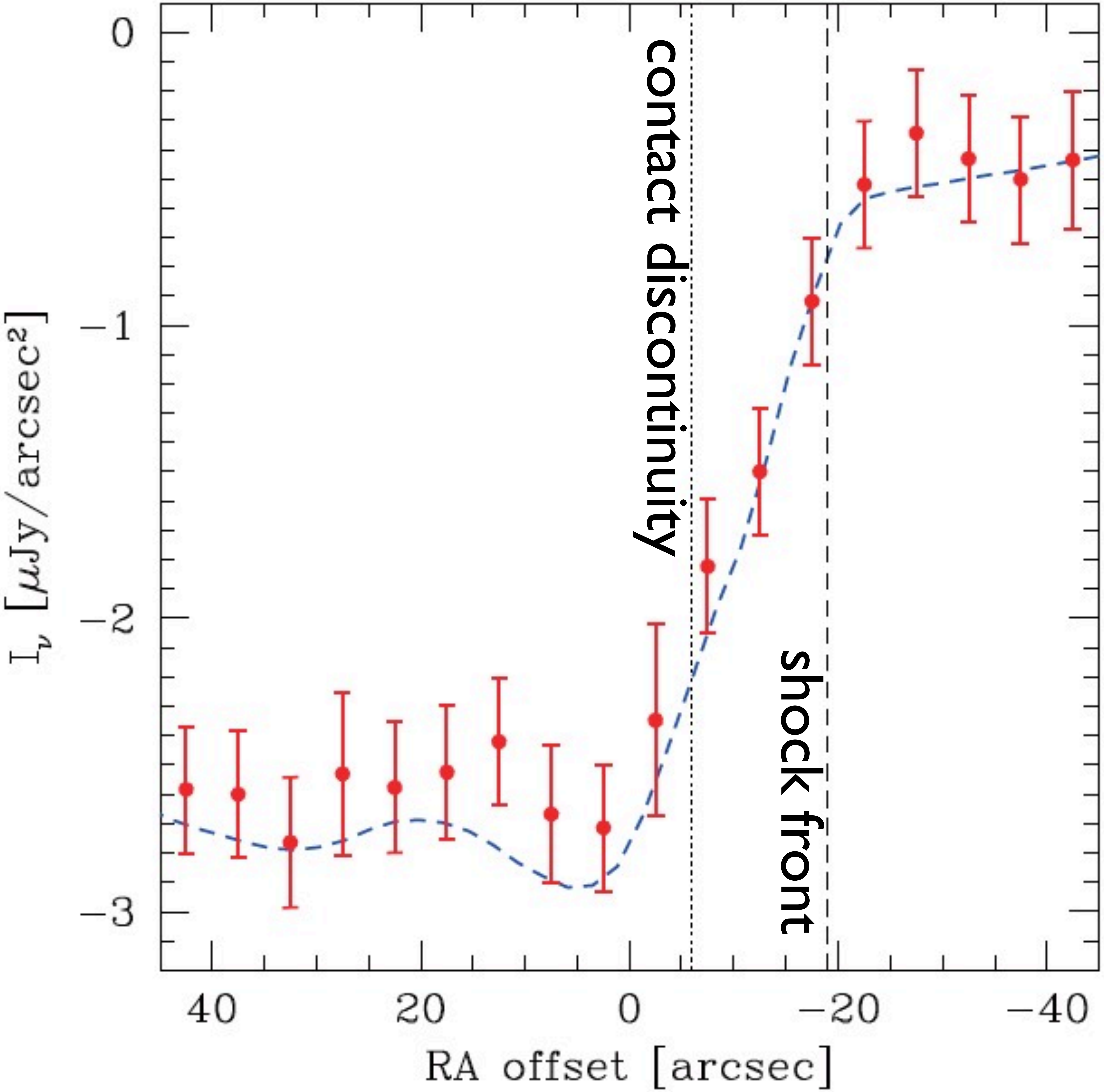
All combined



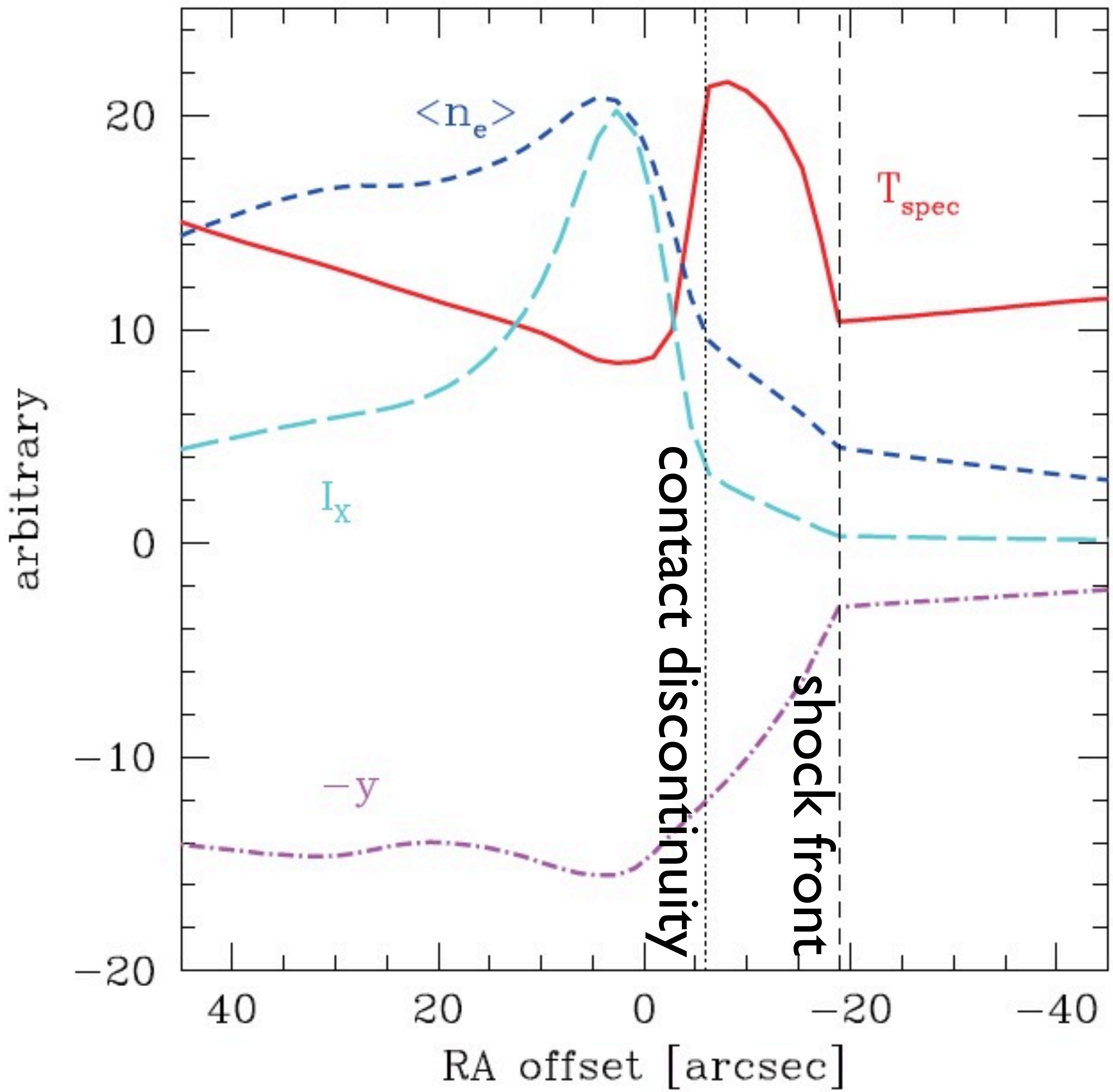
Input SZ image from the Eulerian Simulation of a shock by Takizawa(2005)



All combined



- Good recovery of the profile across the shock!
- Integration time is the same as before, but the observed area is 1/4



- *X-ray and SZ are nicely complementary!*
- SZ increases across the shock front, whereas X-ray does not increase very much.
- X-ray increases across the contact discontinuity, whereas SZ does not increase very much.

Summary

- The high-resolution (~10”) mapping observation of SZ is a powerful (and *proven*!) probe of hot, low-density gas resulting from cluster mergers.
- ALMA is capable of doing this for some clusters, but we would probably have to wait for the next-generation single-dish telescopes such as CCAT to apply these observations to dozens of clusters at high redshift.